Evaluation of Group Factor Method for Analysis of Pile Groups

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SUMMARY:
Among different methods that exist for analysis of soil–pile interaction, the *p–y* method is the most widely used one in practice because it is easy to use and can account for the nonlinear response of soil. It is common practice to use a *p*-multiplier for modifying the single pile *p–y* curve to account for group reduction effects. Use of the *p*-multiplier technique in pile group design relies on the ratio of the pile spacing in the loading direction to the pile diameter and it is defined row by row. The direction of loading changes during the seismic and cyclic loading event. Therefore rather than defining *p*-multipliers row by row, an average *p*-multiplier for all piles in the group is used. This average *p*-multiplier is called group factor. The group factor is obtained through static tests. Group factor is a function of different parameters like pile spacing, soil type, and pile group size. In this study group factors for pile groups with different pile spacings are calculated and the effect of spacing on the group factor is investigated.

Keywords: pile group, p–y curve, group factor, continuum model

1. INTRODUCTION

Pile foundations are used widely in special structures like bridges, high-rise buildings and towers. In practice, piles are sometimes used as single piles to transfer loads to a stronger and deeper soil layer, but they are generally used in groups. For designing a pile, vertical loads are important but in addition to vertical loads significant lateral loads may be present and must be taken into account. These lateral loads can come from a variety of sources, such as wind force, collision, wave or ice impact, earthquake shaking and slope failure.

Although a pile group strengthens the overall lateral load resistance it can weaken the individual pile response in it because of the "group effect". The term group effect refers to the fact that a group will generally exhibit less lateral capacity than the sum of the lateral capacities of the individual piles. This happens because each pile in a pile group affects the soil resistance around other piles. Although some methods have been developed for predicting the lateral response of single piles, there is little information to guide engineers in the design of closely spaced pile groups. Because of the high cost and difficulty of conducting lateral load tests on pile groups, only a few full scale load test results are available that show the distribution of the load within a pile group (Meimon et al., 1986; Brown et al., 1987; Brown et al., 1988; Ruesta and Townsend, 1997; Rollins et al., 1998; Christensen, 2006). In all of these tests and under the same loading, the leading row has the highest resistance in the group but individually these piles have lower resistances than a single isolated pile. The piles in the other rows have lower resistances. The gaps that form behind the piles also assist in decreasing the resistance of the piles.

The lateral response of piles is typically analyzed using a beam on a nonlinear Winkler foundation model. In this approach the pile is modeled as a beam, and the soil is modeled using nonlinear springs that are attached to the pile. The nonlinear springs are defined using API *p–y* curves at regular depth intervals, where *p* represents the lateral soil resistance per unit length of the pile and *y* is the lateral deflection of the pile (API, 2007). As it was discussed before response of a single pile is different from response of a pile in a pile group due to group effect. One of the most common methods of accounting for the group effects is to modify the single pile *p–y* curve using a *p*-multiplier, as suggested by Brown et al. (1988). In this approach, the soil resistance, *p*, is scaled down by a constant factor, P_m, as shown in Fig. 1. The appropriate *p*-multiplier depends on a number of factors such as pile spacing, row position in the group, and soil type.

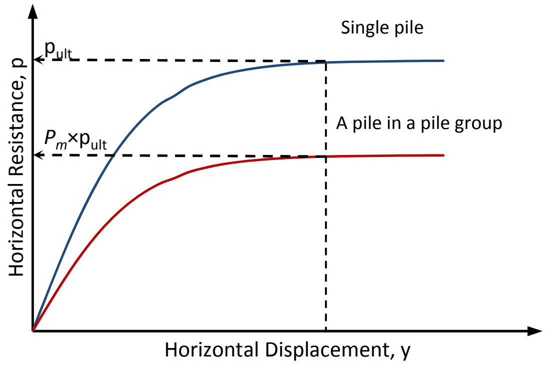

Figure 1. *p*-multiplier (P_m) definition

The *p*-multiplier in pile group design relies on the row spacing in the loading direction. The *p*-multiplier for a leading row is higher than the *p*-multiplier for trailing row. In another approach, rather than defining *p*-multipliers row by row, an average *p*-multiplier for all piles in the group is used (Brown et al., 2001). This *p*-multiplier is called group factor. Use of a group factor is justified for seismic and cyclic loading on the basis that the direction of loading changes constantly and often unpredictably during the loading event and that load reversals occur, converting leading rows of piles with high *p*-multipliers instantaneously into trailing rows with low *p*-multipliers (Brown et al., 2001).

Group factor can be obtained using full scale tests. Full scale tests have the advantages of real piles, real soil, and realistic soil-pile condition. It is however very difficult and expensive to perform a full scale test on a pile group and the capacity of the loading equipment also limit the size of the pile groups; therefore usually the tests are carried out on small pile groups with close spacings. These limitations justify using some advanced numerical simulations to study the pile groups. In order to use a numerical model, it should be validated first. In this study a continuum numerical model is validated using a full scale test performed by Christensen (2006). Then the validated model is used to study the applicability of group factor concept and the effect of pile spacing on the group factor. For this purpose responses of three pile groups with different spacings are modeled using the continuum model. The same system is also simulated using *p–y* model and the required group factor for the *p–y* model is found so that the computed displacements from the *p–y* model match the measured ones from the continuum model for the same pile head force. Finally the bending moments along the pile shafts are calculated using both models and the results are used to study the reliability of the overall concept of group factor analysis of these pile groups at different pile spacings.

2. MODEL VALIDATION

This section briefly explains the validation process of the continuum model based on an existing full scale test result. Christensen (2006) performed a full scale test on a single pile and a 3×3 pile group of steel piles in sand. In this test the outer diameter of pile was 0.324 m, and the piles were spaced at the distance of 5.65 pile diameters (1.83 m) center to center in the direction of loading. The pile spacing perpendicular to the loading direction was 3.29 pile diameters (1.07 m) center to center. Because of the angle iron used to protect the strain gages, the center piles in each row had a moment of inertia of 1.43×10^8 mm^4 about the axis perpendicular to the direction of loading. The remaining six outside piles in the group had a moment of inertia of 1.16×10^8 mm^4. The water table level was observed to be 2.13

m. The pile head condition was free head. The pile group was horizontally pushed to target deflections of 0.006, 0.013, 0.019, 0.025, 0.038, and 0.051 m and pile head forces are measured. Christensen's test results are used for the continuum model validation in our study.

2.1. Continuum model

The pile group response is simulated here using FLAC3D (Itasca, 2009) as a continuum model. Mohr–Coulomb with a non-associated flow rule ($\psi = 0$) is used as the constitutive model for soil. Christensen modeled his pile group test in the GROUP program (Reese et al., 2010) using *p–y* approach. The soil profile in our continuum model is divided into eight layers, as was suggested in the Christensen's *p–y* simulation of the test. Table 1 illustrates soil properties for the model. For elastic properties of the soil, the average soil's Young's modulus for each layer is derived from Christensen's reported CPT test results using equation $E_s=7q_c$ (Bowles, 1996), where E_s is soil Young's modulus and q_c is cone penetration resistance. Poisson's ratio is assumed to be 0.3 for all layers. Shear modulus and bulk modulus are calculated using the Young's modulus and the Poisson's ratio. Unit weight, friction angle, and cohesion for this continuum model are the same as those of Christensen's *p–y* model. The soil parameters for our continuum model are shown in Table 1. Figure 2 shows the measured and computed total pile head force at different pile head target deflections.

Table 1. Input soil properties for the continuum model

Distance from ground surface to top of each soil layer (m)	Unit weight (kN/m^3)	Constitutive model properties				
		Shear modulus (kN/m^2)	Bulk modulus (kN/m^2)	Friction angle (degree)	Cohesion (kN/m^2)	Dilation angle (degree)
0	16.7	29615	64166	40	0	0
2.1	16.7	15884	34416	40	0	0
2.4	19.1	7000	15166	0	41	0
2.7	19.1	7000	15166	0	50	0
3.7	19.1	8076	17500	0	40	0
4.6	18.1	17769	38500	38	0	0
6.3	19.1	6461	14000	0	57	0
8	16.7	22615	49000	33	0	0

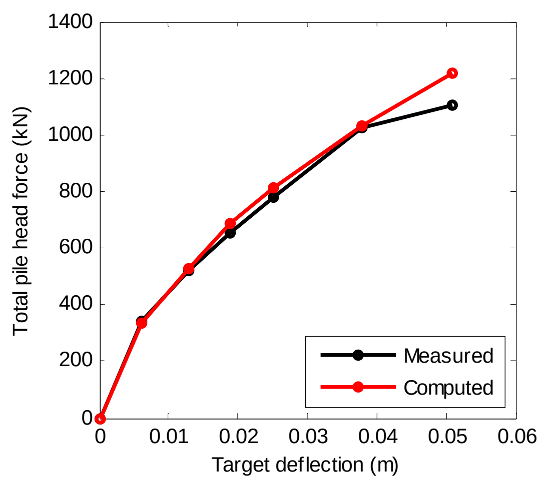

Figure 2. Total pile head force of the pile group at different target deflections from the test and the continuum model

Profiles of bending moments at the target deflections of 0.006 m and 0.051 m are depicted in Fig. 3. Comparisons between the model and the full scale test results show that the continuum model for this test is reliable enough to explore the effects of different parameters on pile group response. For complete details of this model validation see Fayyazi et al. (2012).

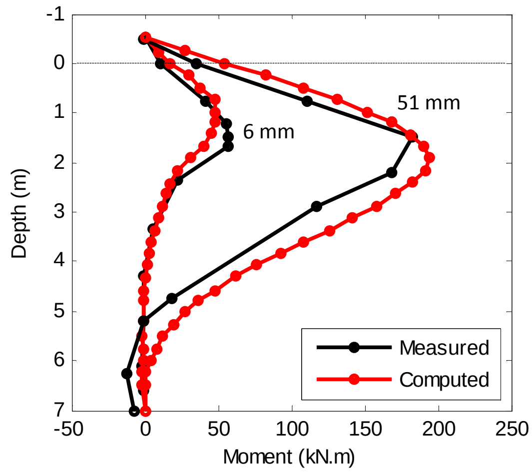

Figure 3. Bending moment profile for the middle pile at different target deflections from the test and the continuum model

2.2. *p–y* model

As it was mentioned before, Christensen (2006) modeled his test in the GROUP program using API *p–y* approach. The computer program GROUP is widely used in practice. He also simulated his single pile test using *p–y* approach. He divided the soil profile to eight layers and he only calibrated properties of the first layer of soil in his *p–y* model using the results of his single pile experiment to get a match on displacement. He used these calibrated parameters for the pile group *p–y* simulations. His soil properties for the *p–y* model are used in this study as described in Table 2. In this table ε_{50} is the strain at 50% of the undrained shear strength. The GROUP program calculates the response for a group of piles using desired input *p*-multipliers. The same procedure of Christensen (2006) is used to obtain the *p*-multipliers. In their procedure the *p*-multipliers are required as input to the program and then they are modified until the computed displacements from the GROUP program match the measured experimental results for the same pile head force. This procedure is repeated for different target deflections. In this study instead of experimental results we used our continuum analysis results to obtain the *p*-multipliers then we compare the obtained *p*-multipliers with Christensen's *p*-multipliers to investigate reliability of our procedure for obtaining *p*-multipliers and also to investigate how much difference in *p*-multipliers we get. Figure 4 shows the pile arrangement in a 3×3 group. The calculated *p*-multipliers for different target deflections and the average *p*-multipliers for each row of the pile group are presented in Table 3. The average *p*-multipliers for this pile group are 1.01, 0.74 and 0.61 for row #1, row #2, and row #3, respectively. These values are in a good agreement with Christensen's (2006) values of 1, 0.7, and 0.65 which are obtained using the pile group full scale test and the GROUP program. This confirms the fact that the *p*-multiplier for a leading row is higher than the *p*-multiplier for trailing row. It is noted that in one case the *p*-multiplier slightly exceeded unity. This means in that case API *p–y* curves were softer than the continuum model so it needed to be stiffened.

From these comparisons it can be concluded that our continuum and *p–y* models are reliable for simulating behavior of pile groups. In the next step a parametric study has been conducted to investigate reliability of using group factor for pile group analysis.

Table 2. Input soil properties for the *p–y* model (Christensen, 2006)

Distance from ground surface to top of each soil layer (m)	Effective Unit weight (kN/m^3)	Subgrade Modulus (kN/m^3)	Friction angle (degree)	ε_{50}	Cohesion (kN/m^2)
0	16.7	7.5E4	40	-	-
2.1	6.7	4.2E4	40	-	-
2.4	9.1	2.7E4	-	0.010	41
2.7	9.1	1.4E5	-	0.010	50
3.7	9.1	2.7E4	-	0.010	40
4.6	8.1	2.6E4	38	-	-
6.3	9.1	1.4E5	-	0.010	57
8	6.7	1.5E4	33	-	-

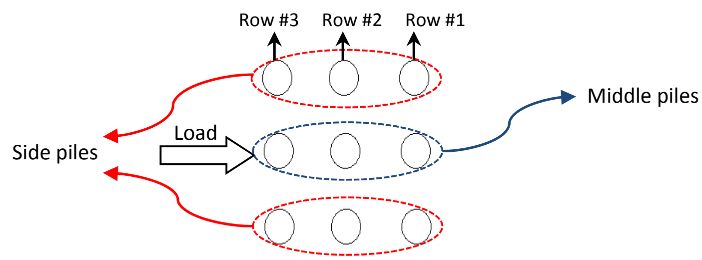

Figure 4. Pile group arrangement

Table 3. Calculated *p*-multipliers for each row of the pile group using the *p–y* model and the continuum model

Pile head deflection (m)	Row#1		Row#2		Row#3	
	Force (kN)	P_m	Force (kN)	P_m	Force (kN)	P_m
0.025	258	1.00	213	0.73	172	0.59
0.038	327	1.03	260	0.74	215	0.60
0.051	369	0.99	295	0.74	369	0.63
		Avg. :1.01		**0.74**		**0.61**

3. PARAMETRIC STUDY

As discussed in Section 1, rather than defining *p*-multipliers row by row, a group factor is used in practice for the pile group analysis. Different 3×3 pile groups with different Spacing over pile Diameter ratios (*S/D*) of 3, 4 and 5 are analyzed using both continuum model and *p–y* model. Pile group dimensions are depicted in Fig. 5. The soil profile for this study is the same as soil profile described in Section 2. Spacings in both directions are the same for each pile group. In the continuum model, the same target deflection at the pile head is applied on all of the piles. Total force at the pile head is calculated and then this force is applied on the head of the pile group in *p–y* model. The group factor is introduced as input to the GROUP program and then it is modified until the computed total pile head deflection for that spacing matches the applied pile head deflection in the continuum model. This procedure is repeated for 3 pile head target deflections (0.03, 0.04 and 0.05 m). In the next step the average of the group factors is calculated and introduced as group factor for that pile group. Calculated group factors for the pile groups with *S/D* of 3, 4 and 5 are presented in Table 4. The group factor increases with the increase of pile spacing; this happens because the group effect decreases with the increase of pile spacing in the pile group.

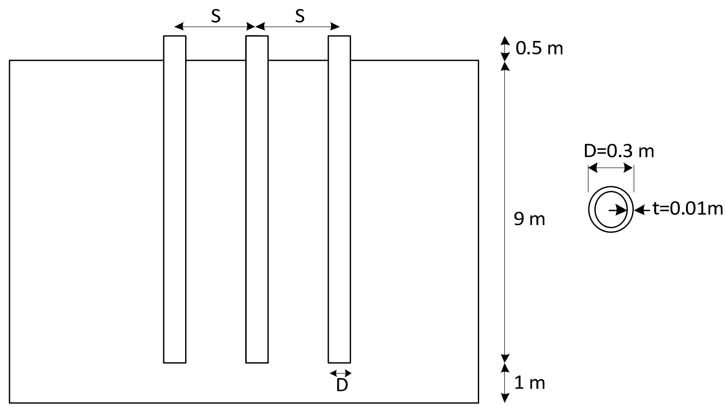

Figure 5. Pile group dimensions for the parametric study

Table 4. Calculated group factors at different pile head deflections for the pile groups with various *S/D* ratios

S/D	Pile head deflection of 0.03 m	Pile head deflection of 0.04 m	Pile head deflection of 0.05 m	Average
3	0.45	0.48	0.51	0.48
4	0.54	0.58	0.60	0.57
5	0.63	0.65	0.68	0.65

For the pile groups with different spacings, the average calculated group factor from Table 4 is used in *p–y* model analysis. The average group factor is calculated for maximum deflection of 0.05 m. The same head deflection is applied on both continuum model and *p–y* model. Results of loading with target deflections of 0.03 m and 0.05 m for different pile groups are reported in this paper. Although average group factor is used for both cases, total pile head force for each target deflection obtained from the *p–y* model using group factor is relatively close to the total force obtained from the continuum model. This is expected because the group factor is calculated based on comparing the total pile head forces obtained from these two models. Although total pile head forces in both methods are very similar, the difference of maximum bending moment is significant. The maximum bending moment difference in each pile is different based on the pile position in the pile group. In the *p–y* model, the same group factor is used for all the piles so all the piles in *p–y* model have identical response.

Difference between maximum bending moment of a pile in *p–y* model and continuum model is equal to $(M_{max,p}-M_{max,c})/\ M_{max,p}\times100$. In this equation $M_{max,p}$ is the maximum bending moment calculated in *p–y* model and $M_{max,c}$ is the maximum bending moment obtained using continuum model. This difference for middle pile and side pile are close to each other. Figures 6 (a, b) show sample results of bending moment profiles at the target deflections of 0.03 m and 0.05 m for the side piles of different rows in a pile group with 3*D* spacing. In these figures the bending moment profile obtained from the *p–y* model is shown by a dashed line. As can be seen, maximum bending moment for the trailing rows is overestimated in the *p–y* model analysis using group factor. This figure shows that for spacing of 3*D, p–y* model can fairly predict bending moment profile for the leading row at lower deflections. With increasing the deflection there is about 15% underestimation for maximum bending moment of the leading row.

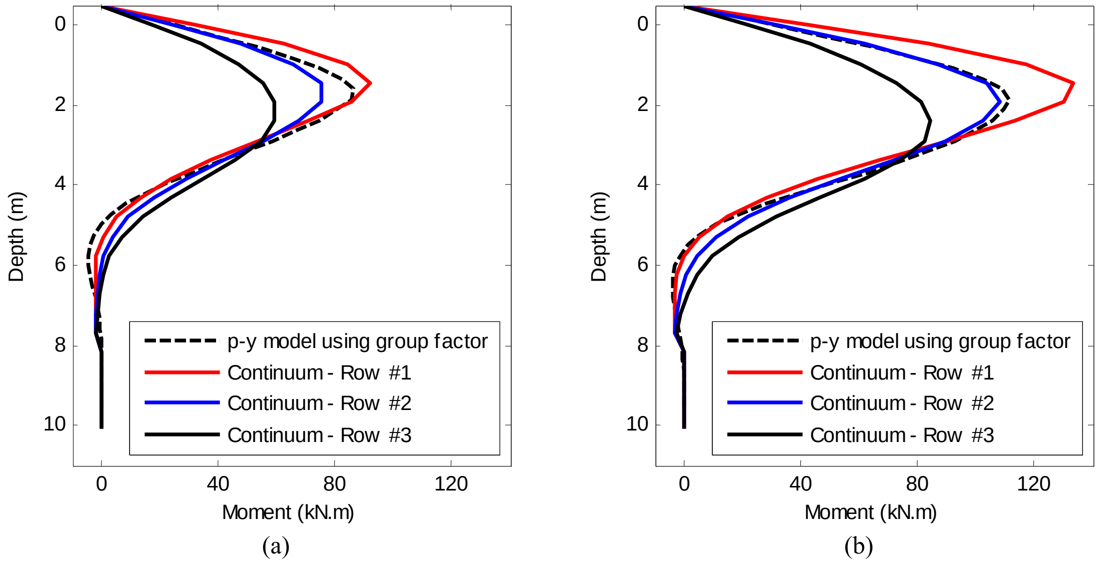

Figure 6. Bending moment profile at target deflections of (a) 0.03 m and (b) 0.05 m for the side piles of a pile group with the spacing of 3*D*

Figure 7 depicts the differences between calculated maximum bending moment using continuum model and using *p–y* model for different piles in the pile groups with different pile spacings. Comparing the amount of these differences at different target deflections shows that with increasing the pile head deflection this difference decreases for almost all of the piles in the group. This reduction is more significant for pile groups with lower spacing. In all cases trailing rows (rows #2 and #3) have higher differences than leading row (rows #1). In all of the pile group configurations with different levels of loading, maximum bending moments are overestimated for trailing rows. However, for row #1 the difference is within fairly acceptable range. As it is shown in Figure 6 leading row always has the highest bending moment, therefore in practice engineers design the piles for maximum bending moment of the leading row.

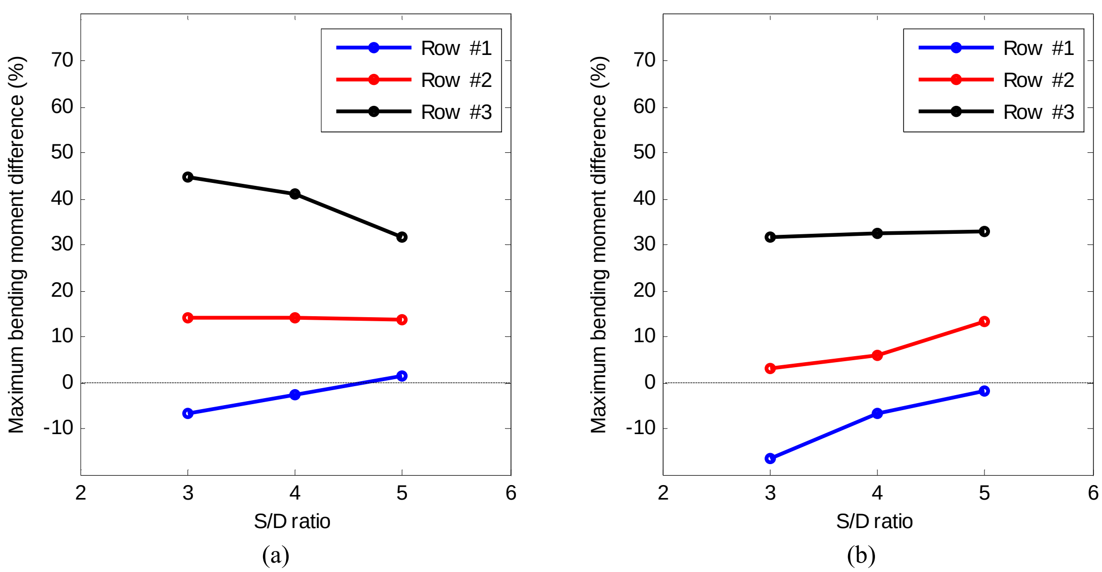

Figure 7. Difference of maximum bending moment at target deflections of (a) 0.03 m and (b) 0.05 m versus pile Spacing/Diameter ratio

Figure 7 illustrates that the amount of difference for piles in the leading row is less than other piles and it is within fairly acceptable range, therefore it can be concluded that the group factor can predict the maximum bending moment for the leading row with acceptable difference. Figure 7 also shows that with increase of spacing, the difference of maximum bending moment between two models decreases for the row #3 at lower deflection. For row #2 at lower deflection this difference does not change significantly with increasing of pile spacing but for higher deflection this difference increases. From Fig. 7 (a,b) it can be concluded that with increase of spacing the amount of difference in maximum bending moment between *p–y* model and continuum model for trailing rows (rows #2 and #3) reaches to the similar value for different target deflections.

4. SUMMARY AND CONCLUSION

A continuum model is validated based on a full scale test which was conducted by Christensen (2006). Group factor for pile groups with different spacings are then calculated based on this validated continuum model approach and the corresponding *p–y* models. The results are used for study the reliability of using group factor for analysis of pile groups with different pile spacings. The same pile head deflection is applied on the *p–y* model and the continuum model and pile head force and bending moment along the pile shafts are calculated for each pile. It is observed that with increase of the loading level the difference of maximum bending moment between continuum model and the corresponding *p–y* model decreases. This evaluation also shows that for different spacings and different target deflections the group factor overestimates the maximum bending moment for the trailing rows. The amount of overestimation for the last trailing row is considerable. The amount of overestimation for the middle row is about half of the last trailing row.

In practice engineers design the pile for maximum bending moment of piles in the leading row which is the highest bending moment in the pile group. In this study it is shown that for different pile group settings and different target deflections the predictions of the *p–y* model for maximum bending moment of the leading rows are relatively close to those of the continuum model. Therefore use of group factor is reasonable for design and analysis of a pile group. This research also showed that even with using specific group factor which is obtained exactly for a specific pile group, there will be noticeable errors for prediction of maximum bending moments of trailing rows. Since there is no specific recommendation in practice for choosing the group factor, analyses are now underway to provide a basis for selecting group factors for different pile group configurations and soil types.

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