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EVALUATION OF P-MULTIPLIER METHOD FOR PERFORMANCE-BASED DESIGN OF PILE GROUPS

M. Sajjad FAYYAZI[1], Mahdi TAIEBAT[2], W.D. Liam FINN[3], and Carlos E. VENTURA[4]

ABSTRACT

Criteria for the Performance-Based Design (PBD) in pile foundations are expressed in terms of limiting values of the response parameters of the pile foundations such as the pile head horizontal displacement. The analysis method for soil–pile interaction significantly affects the predicted response of pile-supported structures; therefore, the method in which soil–pile interaction is simulated is very important for PBD. Among different methods that exist for analysis of pile groups, *P*-multiplier method is the most widely used in practice. In the proposed *P*-multipliers in practice, the influence of pile spacing in the same row, which is normal to the loading direction, is usually ignored. In this paper, first the influence of row by row spacing and influence of spacing in a row on the response of a pile group are evaluated separately and compared with each other. Then for observing the influence of spacing in a row in a real pile group, response of a 3×3 pile group is analyzed using a continuum model. The analytical results are compared with data from a full scale pile group test to investigate the reliability of the continuum model. Then, using continuum model, the effect of changing the spacing in a row is evaluated to see the difference.

Keywords: Pile group, *P*-multiplier, Lateral loading, Soil pile interaction

INTRODUCTION

In North American building codes (e.g., NBC, 2005; FEMA 356, 2000; and SEAOC, 1995), the design philosophy for earthquake loading is to accept some level of damage to structures, i.e., to accept some level of deformation. The acceptable level of damage and deformation is a function of the type and importance of the structure and the earthquake return period (Robertson, 2009). Therefore, evaluation of deformations is a key parameter in any performance-based design. Foundations of many important structures supported by unreliable soil include pile groups. The analysis method for soil–pile interaction significantly affects the predicted response of pile-supported structures. Therefore, the method in which soil–pile interaction is simulated is very important for Performance-Based Design (PBD). Although fairly reliable methods have been developed for predicting the lateral capacity of single piles under static loads, there is very little information to guide engineers in the design of closely spaced pile groups with spacing less than about six pile diameters. Because of the high cost and logistical difficulty of conducting lateral

[1]Research Assistant, Department of Civil Engineering, University of British Columbia, Vancouver, Canada, e-mail: sfayyazi@civil.ubc.ca
[2]Assistant Professor, Department of Civil Engineering, University of British Columbia, Vancouver, Canada, e-mail: mtaiebat@civil.ubc.ca
[3]Emeritus Professor, Department of Civil Engineering, University of British Columbia, Vancouver, Canada, e-mail: finn@civil.ubc.ca
[4]Professor, Department of Civil Engineering, University of British Columbia, Vancouver, Canada, e-mail: ventura@civil.ubc.ca

load tests on pile groups, only a few full scale load test results are available that show the distribution of 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). These tests have all involved static or quasi-static loadings. Nevertheless, the data from these limited field tests indicate that piles in groups will undergo significantly more displacement and higher bending moments for a given load per pile than will a single isolated pile. In the pile group, the overall lateral load is divided among each of the piles in the group. Each pile pushes against the soil in front of it, creating a shear zone in the soil. These shear zones begin to enlarge and overlap as the lateral load increases. More overlapping occurs if the piles are spaced very close to each other in both rows and columns.

"Edge effects" is used to describe the effects of overlapping zones of influence occurring between two piles in the same row, and when overlapping occurs between piles in different rows it is known as "shadowing effects." All of these "group interaction effects" result in less lateral resistance per pile. Figure 1 displays the shear zones and the various group effects that occur within a laterally loaded pile group. The leading row of piles has the highest resistance of any of the rows in the group, since it experiences only edge effects. The piles in the leading row are therefore only slightly less resistant than a single isolated pile under the same loading. The piles in the other rows have even lower resistance because they experience edge effects and shadowing effects. The gaps that form behind the piles also assist in decreasing the resistance of the piles behind them.

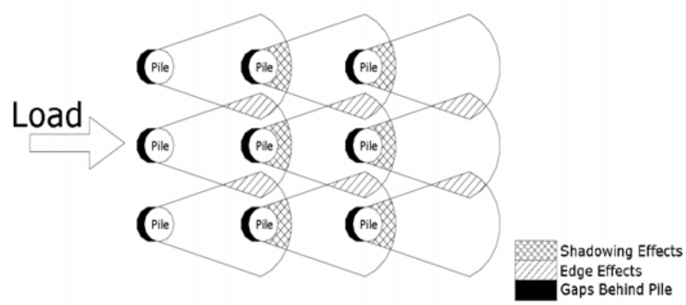


Figure 1. Illustration of shadowing and edge effects in a laterally loaded pile group (After Walsh, 2005).

The lateral response of piles is typically analyzed using *p–y* methods. 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 *p–y* curves at regular depth intervals, where *p* represents the lateral soil resistance per unit length of the pile and the *y* is the lateral deflection of the pile. One the most common methods of accounting for the group reduction effects is to modify the single pile *p–y* curve using a *P*-multiplier, as suggested by Brown et al. (1988). With this approach, the soil resistance, *p*, is scaled down by a constant factor, *P*, as shown in Figure 2. In this figure p_{SP} is the ultimate horizontal resistance of the soil for single pile and p_{GP} represents the ultimate horizontal resistance of the soil for a pile in a pile goup. The appropriate *P*-multiplier is likely dependent on a number of factors, such as pile spacing, row position in the group, and soil type.

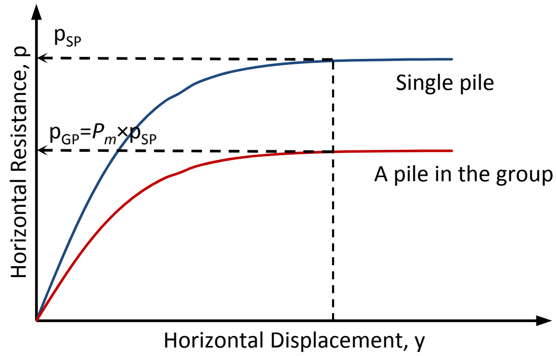


Figure 2. *P*-multiplier (*P_m*) definition

Because of the dearth of experimental data, computer programs for pile groups have not been thoroughly validated, and empirical methods such as those using *P*-multipliers are extremely restricted in their application. For example, *P*-multipliers from full scale tests are mostly available for spacing of three pile diameters and typically for three rows or less. At present, the use of the *P*-multiplier technique in pile group design relies only on the ratio of the pile row spacing in the loading direction to the pile diameter (S_L/D). However, the suggested *P*-multipliers could be affected by (1) the influence of pile spacing in the direction that is transverse to the loading direction (S_T); (2) level of lateral loading; and (3) pile arrangements (Ashour and Ardalan, 2011). Currently, the *P*-multiplier is used as a function of pile row spacing in the loading direction, S_L (USACE, 1993; AASHTO, 2007). This means the edge effect (due to S_T) is not well accounted for. An interpolation between suggested *P*-multipliers should be conducted to determine the *P*-multiplier for other pile spacings, as is the case in AASHTO (2007), which provides *P*-multipliers for only 3*D* and 5*D* pile-row spacings, where *D* is pile diameter.

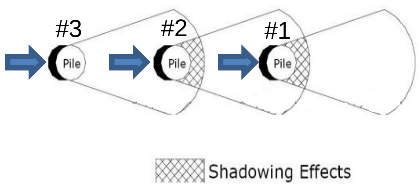
Considering these simplifications and lack of data, engineers are forced to design pile groups in a very conservative manner to deal with the uncertainty. In this paper effects of S_L and S_T are compared for two different levels of loading. In the next step the goal of this paper is to show the difference between pile group responses when the spacing in a row (S_T) changes. Evaluating this difference will show the influence of the edge effect on the pile group reaction. This will be done by modeling a full scale pile group test (Christensen, 2006) using FLAC3D finite difference program (Itasca Consulting Group, Inc., 2009). The analytical results will be compared with full scale test data to investigate the reliability of the continuum model. Then, by changing the S_T in the model this effect will be evaluated.

EVALUATION OF SHADOWING EFFECT AND EDGE EFFECT

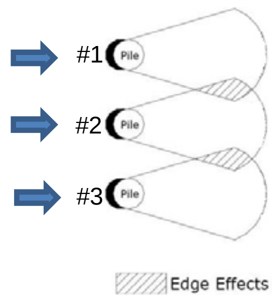
For evaluating influence of edge effect and shadowing effect on the response of a pile group separately, two different pile groups are modeled in sand. For evaluating influence of shadowing effect three piles are modeled in a line with direction of loading, Figure 3(a) shows this configuration. For edge effect, three piles in a row are modeled as it is shown in Figure 3(b). Pile diameter is 0.4 m and the pile length is 8 m. The spacing between piles changes from 3*D* to 10*D*. Soil parameters are shown in table 1. Two different levels of displacement are applied on the pile heads. Displacement is applied on the all pile heads equally and forces at the pile heads are measured. The same displacements are applied on a single pile to compare the results with the piles in these two pile group configurations.

Table 1. Input soil properties

Unit weight (kN/m^3)	Shear modulus (kN/m^2)	Bulk modulus (kN/m^2)	Friction angle (degree)	Dilation angle (degree)
1600	373130	38600	35	0



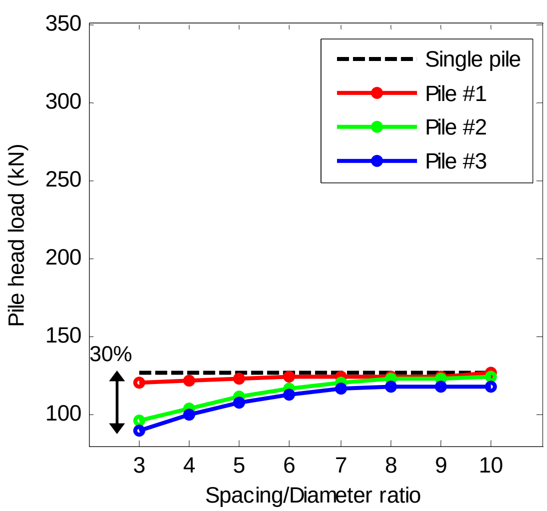
(a) Pile group configuration I



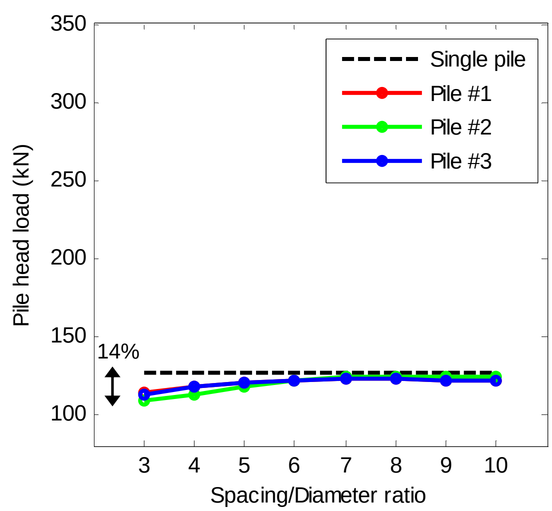
(b) Pile group configuration II

Figure 3. Pile numbering in different pile group configurations

Figure 4 shows the pile head forces for displacement of 0.02 m for different pile configurations. The dashed line shows the single pile head force for the same displacement. Figure 4(a) shows the influence of shadowing effect on the response pile group. It is observed that response of pile #1 is very close to the response of a single pile for all the spacings, this confirms the fact that the leading row takes the most load and behaves similar to the single pile. For the arrangement of piles in a row, because of the symmetry, the response of side piles are the same, therefore in Figure 4(b) forces of pile #1 and pile #3 for different spacings are completely the same. The maximum difference of response caused by shadowing effect between a single pile and a pile in the pile group is 30% and the maximum difference caused by edge effect is 14% so the ratio of maximum influence of shadowing effect to maximum influence of edge effect is about two for small displacement of 0.02 m. Figures 4(a, b) show that this ratio is almost constant for the spacings of 3*D* to 6*D*.



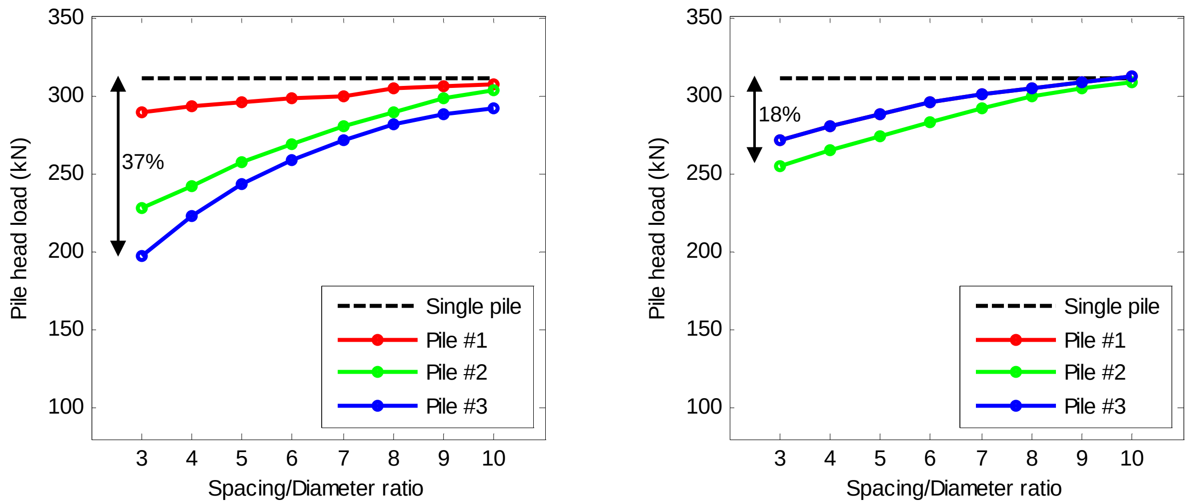
(a) Pile group configuration I



(b) Pile group configuration II

Figure 4. Pile head force of different pile configurations for displacement of 2 cm

In Figures 5(a, b) the displacement level is increased to 0.10 m. It is observed that the ratio of maximum influence of shadowing effect and edge effect is about 2 for the higher level displacement too.



(a) Pile group configuration I (b) Pile group configuration II

Figure 5. Pile head force for different pile configurations for displacement of 10 cm

Figure 6 shows the average response of the piles in the configuration I (shadowing effect) and average response of pile in configuration II (edge effect) for 10 cm pile head displacement for different spacings. This graph shows that for average response the ratio of influence of these two effects is even less than two. It can be concluded that the influence of edge effect is even more than 50% of shadowing effect influence, this means in the design and analysis of pile groups spacing in a row should be well accounted too.

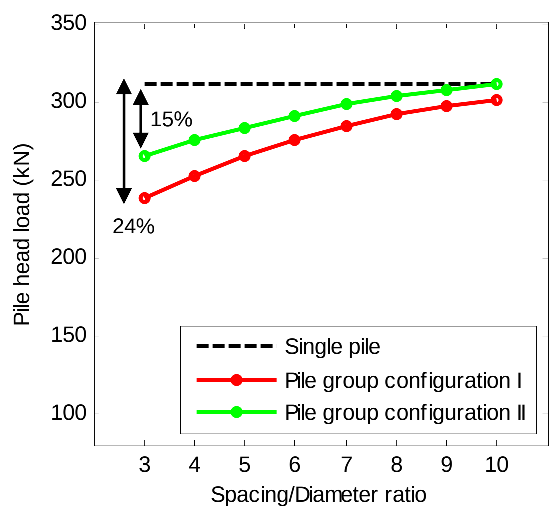


Figure 6. Average pile head force for different pile configurations for displacement of 10 cm

After evaluating shadowing effect and edge effect separately, the influence of edge effect will be evaluated in a 3×3 pile group. For this purpose first a full scale test is analyzed to validate the model and then spacing in a row is changed and results are compared.

MODEL VALIDATION FOR A 3×3 PILE GROUP

Field test

Christensen (2006) performed a full scale test on a 3×3 pile group of steel piles in sand. The outer diameter was 0.324 m, and piles were spaced at 5.65 pile diameters (1.83 m) center to center in the direction of loading. The side by side spacing of the piles within each row was 3.29 pile diameters (1.07 m) center to center perpendicular to the loading, as shown in Figure 7.

There was a large steel load frame around the pile group. The load frame was connected to each of the piles, causing the piles to move together as a group when the load frame was pushed laterally. Each of the piles was connected to the frame using a pinned connection which allowed each pile head to rotate freely. Each pinned connection resulted in a load point 0.48 m above ground level. The single pile and that pile group were horizontally pushed to a number of target deflections. These target deflections were 0.006, 0.013, 0.019, 0.025, 0.038, and 0.051 m. Figure 8 shows the CPT variations of the soil layers in Christensen's study.

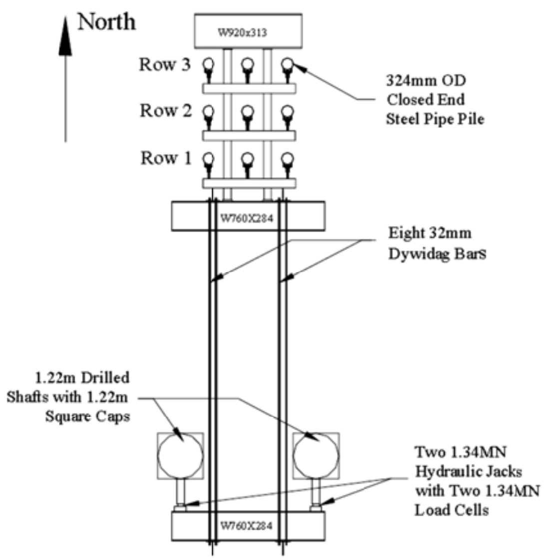


Figure 7. Plan view of the test system (After Christensen, 2006)

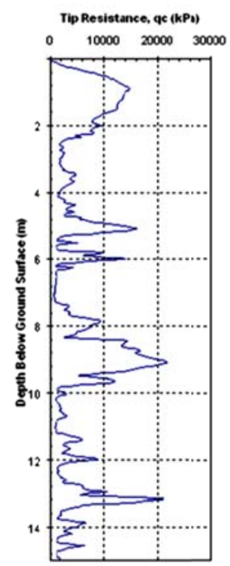


Figure 8. CPT profile of soil (After Christensen, 2006)

Numerical modeling

Christensen also modeled his test using a *p*–*y* model. He divided the soil profile into eight layers in his model. In his study, the measured load-deflection curves are compared with computed ones from the model, when the load-deflection curves did not match, modifications were made to the upper sand layer friction angle and the model results were re-calculated. Iterations continued until the calculated results matched the measured. In this paper the pile group is modeled numerically using a continuum model. The behavior of the soil is modeled using the Mohr-Coulomb model with non-associated flow rule (ψ = 0). The average soil's Young modulus for each layer are derived from Figure 8 using equation $E_s=7q_c$ (Bowles, 1996). Soil layering and other soil parameters for continuum modeling are the same as the values in Christensen's model and are listed in Table 2.

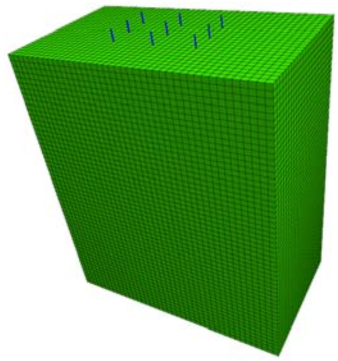


Figure 9. Numerical model mesh

Table 2. Input soil properties for continuum model

Distance from ground surface to top of each soil layer (m)	Unit weight (kN/m^3)	Young's modulus (kN/m^2)	Poisson's ratio	Friction angle (degree)	Dilation angle (degree)	c (kN/m^2)
0	16.7	77000	0.3	40	0	-
2.1	16.8	41300	0.3	40	0	-
2.4	19.1	18200	0.3	-	0	41
2.7	19.1	18200	0.3	-	0	50
3.7	19.1	21000	0.3	-	0	40
4.6	18.1	46200	0.3	38	0	-
6.3	19.1	16800	0.3	-	0	57
8	16.7	58800	0.3	33	0	-

The numerical model mesh is shown in Figure 9. Figure 10 depict the load at different target deflections from the test (measured) and the continuum model (computed). This figure shows that the model can

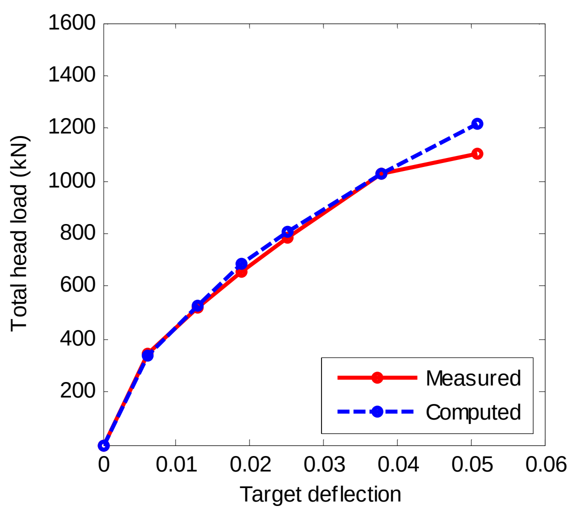


Figure 10. Total head load at different target deflections for pile group

predict the load very well for the pile group. However, with increasing deflection the difference between the computed load and the measured load increases, but this difference is still not very significant.
In the test, the middle pile in row 2 (see Figure 7) was instrumented to measure the bending moment along the pile length. Comparison between measured and computed bending moment profile for this pile in the pile group is shown in Figure 11. This figure shows that for small target deflection (0.006 m) the numerical model can predict the moment quite well. However, for the larger target deflection (0.051 m) the predicted values are not as good as those predicted for the lower deflection, but still the difference is not very significant. After these comparisons between the continuum model and full scale test, it can be concluded that the continuum model results for this test are reliable enough to explore the effect of different parameters in the pile group.

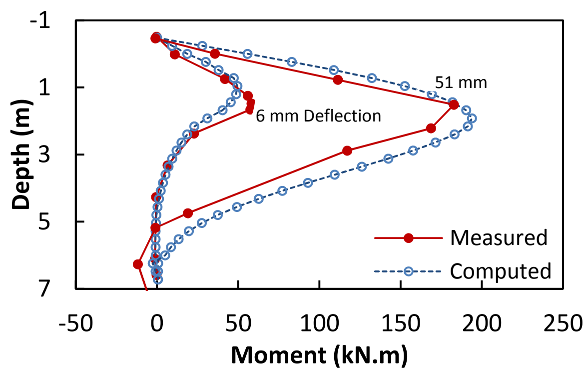


Figure 11. Bending moment profile of the middle pile in pile group

EVALUATION OF EDGE EFFECT IN A 3×3 PILE GROUP

Two other pile groups are analysed using the finite difference method; all the properties in these two models are the same as those of the pile group discussed in the previous section. The only changed parameter is pile spacing in the row. In one of the models the spacing in the row is 2.4*D* (0.78 m) and in the other one this spacing is 5.65*D* (1.82 m), where *D* is pile diameter. All other parameters are the same. Loading target deflections are 0.006, 0.013, 0.019, 0.025, 0.038, 0.051, and 0.07 m.

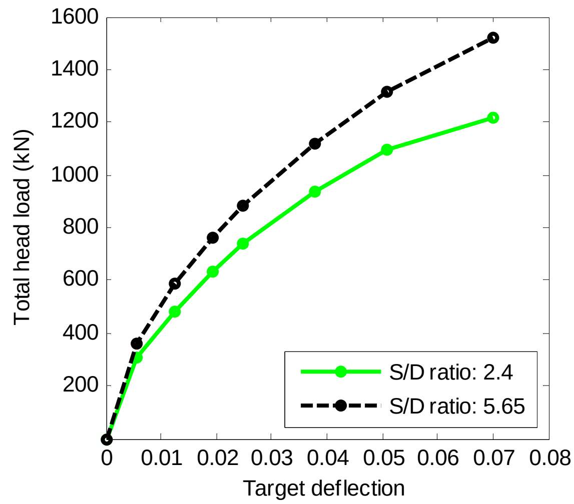


Figure 12. Total head load versus target deflection for pile group with different spacings

Figure 12 shows the total load difference between the two pile groups. As it can be seen, the difference between these two increases with an increase in the deflection. For a relatively small deflection of 0.07 m there is a difference of about 30%. This 30% difference is caused only by different spacing in the row (S_T), because all other parameters in both models are the same.

In practice the use of the *P*-multiplier method for pile group design relies only on the ratio of the row by row spacing in the loading direction to the pile diameter. Therefore, the effect of different spacing in a row is not accounted for. Most of the proposed *P*-multipliers are based on tests with spacing in the row of about 3*D*, but in practice pile spacing commonly varies from 3*D* to 6*D*. Therefore, Figure 12 shows that using the proposed *P*-multiplier for more than 3*D* spacing in the row can cause considerable unconservative error. As it is shown here, this difference for relatively small deflection target of 0.07 m is 30%, obviously for higher deflections this difference will be even more. The difference of maximum bending moment is not as significant as the total head force. This difference is shown at two different target deflection in Figures 13.

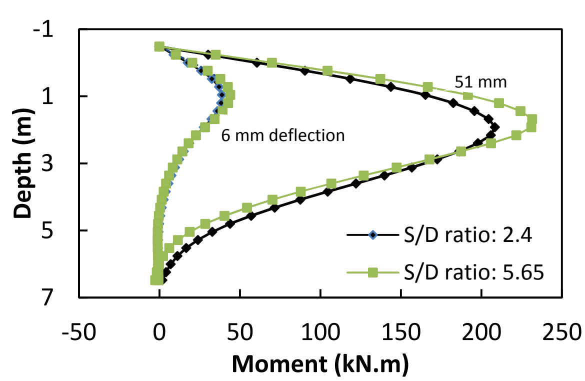


Figure 13. Middle pile of pile group bending moment profile for different spacings

CONCLUSION

Performance-Based Design (PBD) is rapidly becoming the norm for modern seismic design of structures owing to the cost savings that can often be achieved through this approach. Accurate evaluation of deformations is crucial in any performance-based design. The analysis method for soil–pile interaction significantly affects the predicted response of pile-supported structures; therefore, the accuracy and comprehensiveness of the method of analysis is very important for PBD.

At present, when there is no data from a full scale test, the use of the *P*-multiplier method in pile group design relies only on the row by row spacing of the pile group. This means shadowing effect is taken care of in this method but there is not any specific consideration for spacing perpendicular to the direction of loading, which is corresponding to edge effect. This paper has evaluated shadowing effect and edge effect separately in two different pile group configurations and compared their influence. This comparison shows that the difference in response of a pile group due to the edge effect can be even more than 50% of shadowing effect influence, So it should be well accounted for.

In the other part of this paper, it is observed that changing the spacing in the row (S_T) has a considerable effect on the response of a real pile group. Two pile groups with arrangement of 3×3 are analyzed. The only difference of these two pile groups is S_T. Comparing the both of results of analyses for these pile groups shows that ignoring effect of different S_T can cause about 30% difference in load capacity for relatively small deflections. In practice the same *P*-multiplier is used for these two pile groups, but in this paper it is shown that 30% difference in response will be ignored in that procedure. Considering that *p–y* model by itself has considerable error, using the same P-multiplier for pile groups with different S_T can add 30% more error to the total error. Analyses are now underway to provide a basis for selecting *P*-multipliers on the basis of a wide range in both row and column spacing of piles in pile groups and for several different pile group configurations.

ACKNOWLEDGEMENTS

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