Predictions of friction pile group response using embedded piles in PLAXIS

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ABSTRACT: Embedded piles in PLAXIS are piles composed of beam elements where pile-soil interaction is modelled using special interface elements. Although embedded piles do not occupy volume, a particular zone around the embedded pile corresponding to the pile diameter, is maintained elastic. The reduced number of elements required with the use of embedded piles in PLAXIS has the potential to alleviate the computing restrictions often associated with 3-D finite element analyses of large pile groups. In this paper, PLAXIS 3-D Foundation is used to investigate the suitability of embedded piles for the prediction of the behaviour of a single pile and 5-pile group in soft clay. In addition, predictions of conventional 2-pile interaction factors and the settlement performance of large rigid pile groups determined using embedded pile beam elements are compared to a range of field data. Results show that although embedded piles appear to slightly over-predict the extent of pile-to-pile interaction, satisfactory agreement to field data is achieved, thus highlighting the possibility of saving considerable time and computational resources in the use of 3-D finite element analyses with advanced nonlinear soil models.

1 INTRODUCTION

It is now well established that 3-D Finite Element (FE) analysis is the most rigorous tool available in the analysis of pile groups. The FE method can consider the pile-soil system as one composite continuum where pile-soil-pile interaction is considered directly. FE analyses can impose considerable drains on computing resources however, particularly if soil stiffness nonlinearity and nonstandard pile group geometries are to be modelled simultaneously. Because of this, the application of FE analysis to pile groups has been restricted to simplified 2-D analyses (e.g. McCabe and Lehane 2006) or 3-D analyses of small groups (e.g. Sheil and McCabe 2012a).

The ‘embedded pile’ feature in PLAXIS presents an opportunity to alleviate some of the computing restrictions associated with 3-D FE analyses using nonlinear soil models. Embedded piles are piles composed of beam elements. The number of elements in the FE model is thus greatly reduced when using embedded piles compared to volume piles where the entire volume of the pile is discretised. Although embedded piles do not occupy volume, a particular radius around the axis of the embedded beam corresponding to the pile radius, is maintained elastic; thus simulating the behaviour of volume piles. Engin et al. (2008) validated the use of embedded piles for the prediction of the load-displacement response of a single pile in both compression and pull-out tests. The behaviour of a piled raft was also compared to field data with satisfactory agreement.

In this paper, embedded piles in PLAXIS 3-D Foundation are used to predict the behaviour of a single pile and pile group load test carried out in soft clay at a geotechnical test site in Kinnegar, Belfast reported by McCabe and Lehane (2006). The advanced nonlinear Hardening Soil (HS) model is employed in the present paper. This model was validated by Sheil and McCabe (2012b) where the authors compared the behaviour of 'volume' piles in PLAXIS 3-D Foundation using the HS model to the same load tests with good agreement. A description of the Kinnegar test site and the corresponding soil properties adopted in the present soil model are documented by Sheil and McCabe (2012b). A brief description of the salient features of embedded piles is provided. In addition, predictions of two-pile interaction factors and the stiffness efficiency of rigidly-capped pile groups using embedded piles are compared to a range of field data. With the reduced number of elements associated with embedded piles, predictions of the settlement performance of much larger pile groups is possible where groups of up to 1000 piles is considered in the present study.

2 FINITE ELEMENT MODELLING

2.1. Embedded pile elements

The embedded pile beam elements are 3-node line elements with three translational degrees of freedom and three rotational degrees of freedom at each node. Element stiffness matrices are numerically integrated from the four Gaussian integration points. These elements allow for deformations of the beam (pile) due to shearing, bending and compressive and tensile axial forces.

Pile-soil interaction is modelled using special interface elements which involve a skin resistance and a foot resistance; unlike volume piles however, pile-soil interaction is modelled at the centre of the pile instead of the pile circumference. The pile beam elements can cross a 15-node wedge element at any place and with any direction as shown in Figure 1. Virtual nodes (denoted by the blank circles) are introduced into the soil volume at the beam element nodes and a special interface forms a connection between the nodes of the beam element and the virtual nodes (and thus the nodes of the soil volume element).

2.2. Embedded pile bearing capacity

Unlike volume piles in PLAXIS, the bearing capacity of an embedded pile is not a result of FE calculations but is considered an input parameter. The behaviour of the special embedded interface elements are described by an elastic-plastic model. An input of the maximum skin resistance, T_{max}, and base resistance, F_{max}, is required and are usually derived from pile load test data. The behaviour of the interface (i.e. elastic behaviour or plastic behaviour) for both the skin and base resistance is determined by a failure criterion. Elastic interface behaviour only allows small relative pile-soil displacement whereas pile-soil slip may occur during plastic interface behaviour. The skin resistance profile can be defined in three different ways:

(i) **Linear** – Skin resistance is defined by the maximum skin resistance at the pile head ($T_{top,max}$) and the maximum skin resistance at the pile bottom ($T_{bot,max}$)

(ii) **Multi-linear** – This option can be used to take into account different layers with different resistances. The maximum skin resistance (T_{max}) is defined at different positions along the length of the pile, L.

(iii) **Layer dependent** – The third option can be used to relate the embedded pile skin resistance to the strength properties of the soil (cohesion, c, and friction angle, φ') and the interface strength reduction factor, R_{inter}. An overall maximum skin resistance is specified to prevent the capacity of the embedded pile reaching undesired high values.

2.3. Embedded pile properties

The embedded pile properties that have been adopted in the present study are presented in Table 1. For the (concrete) embedded pile a Young's modulus of 30 GPa and a unit weight of 25 kN/m^2 were chosen. A pile diameter, D, of 0.282 m and length, L, of 6 m were selected based on the equivalent pile diameter and pile length of the single and group pile load tests reported by McCabe and Lehane (2006). A simplified uniform 'linear' skin resistance profile was selected where the maximum skin resistance T_{max} and base resistance F_{max} were derived from the single pile bearing capacity documented by McCabe (2006) presented in section 3.1. The pile-soil interaction parameters presented in Table 1 relate to the bearing capacity of the pile only and do not incorporate the stiffness response of the pile. The stiffness response of the soil also involves the stiffness of the soil layers in which the pile is situated.

Table 1. Embedded pile properties

E	GPa	30
γ	kN/m^3	25
D	m	0.282
Skin resistance		Linear
$T_{top,\,max}$	kN/m	9
$T_{bot,\,max}$	kN/m	9
F_{max}	kN	10
Pile length	m	6

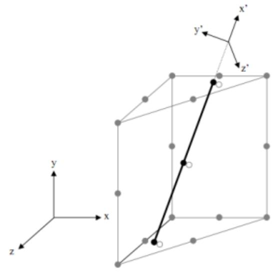

Figure 1. Illustration of beam element (pile) crossing 15-node wedge element (Brinkgreve, 2007)

2.4. Stages of analysis – single pile

The stages of analysis used in the simulation of the single pile load test by McCabe and Lehane (2006) are such as to represent, as closely as possible, the sequence of events undertaken at the test site and are defined as follows:

(i) Initial stress generation by the K_0 procedure, a special calculation method available in PLAXIS.
(ii) Installation of the pile reflected by 'turning on' the embedded beam (pile) in the model.
(iii) Pile loading by placing a point load on the top of the embedded pile.
(v) Recording of the pile head displacement versus pile head load relative to the start of loading.

2.5. Stages of analysis – pile group

For the case of pile groups connected to a rigid pile cap a slightly different procedure was followed:
(i) - (ii) Similar procedure to that described in section 2.4.
(iii) Installation of the pile cap (modelled as a 'floor' in PLAXIS) along the top of the pile group. A Young's modulus of 30 GPa and a Poisson's ratio of 0.15 were selected in order to simulate a concrete pile cap while a depth of 0.3 m was selected as the thickness.
(iv) Pile group loading by placing a compressive uniform distributed load along the top surface of the pile cap.
(v) Recording of the pile cap displacement versus pile head load relative to the start of loading

The pile groups considered in the present study are free-standing groups; thus the pile cap does not come into contact with the ground surface. A depth of 0.5 m was maintained between the level of the pile cap and the ground surface. The depth below ground level to the base of the piles is maintained the same as that in the analyses of a single pile.

2.6. Stages of analysis – two-pile interaction factors

The interaction factor (α) is defined by Poulos (1968) as:

$$\alpha = \frac{S_{ij}}{S_{ii}} \qquad (1)$$

where S_{ij} is the additional settlement of pile *i* due to a nearby loaded pile *j* and S_{ii} is the settlement of pile *i* under its own load. For the calculation of interaction factors in the present paper, the settlement of a single pile under its own load was first determined by PLAXIS analyses. A non-loaded pile was then placed within the settlement field of a loaded pile at a number of different pile spacing to diameter ratios (*S/D*). The 'interactive' settlement of the non-loaded pile due to the presence of the neighbouring loaded pile was then recorded for each value of *S/D* and the corresponding value of α calculated.

2.7. Mesh sensitivity analysis

5 different meshes with different levels of refinement were applied to check the sensitivity of the mesh refinement on single pile settlement predictions. Figure 2 presents an illustration of the 5 different FE meshes considered. From Figure 3, a convergence in results is evident.

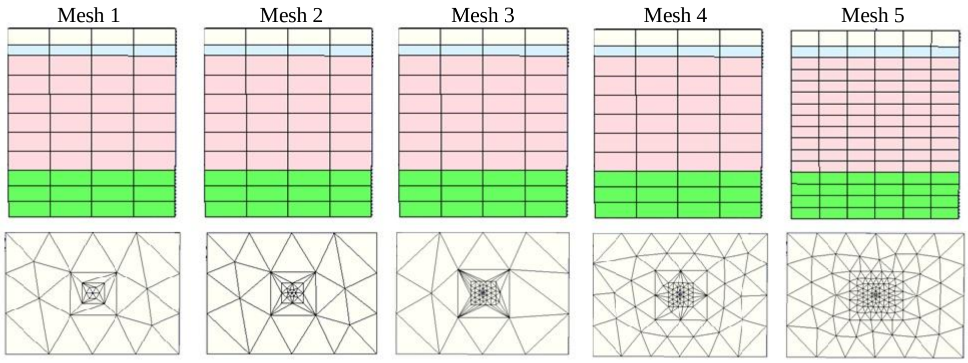

Figure 2. The FE meshes used in the 3-D analyses

3 EMBEDDED PILE RESULTS

3.1. Single pile and pile group load displacement response

The ability of the embedded piles in PLAXIS to predict the behaviour of a single pile and 5-pile group load test in soft clay reported by McCabe and Lehane (2006) has been investigated. It can be seen from Figure 4 that the embedded piles together with the adopted nonlinear soil model (details documented by Sheil and McCabe (2012a)) predict the stiffness of the single pile reasonably well up to a Factor of Safety (FOS) of ~1.5. As mentioned in section 2.6, the ultimate shaft and base resistance of the embedded piles were calibrated against the capacity of the single pile documented by McCabe and Lehane (2006). It must also be noted, however, that when embedded piles are placed in a group, the group action must also be taken into account when defining the pile bearing capacity. McCabe and Lehane (2006) noted, however, that the average group pile bearing capacity was approximately equal to the single pile bearing capacity. Thus the embedded pile properties adopted for the single pile reported in Table 1 have also been selected for the group piles. From Figure 4, the embedded piles also show satisfactory agreement to the load-displacement response of the 5-pile group up to a FOS on capacity of ~1.5.

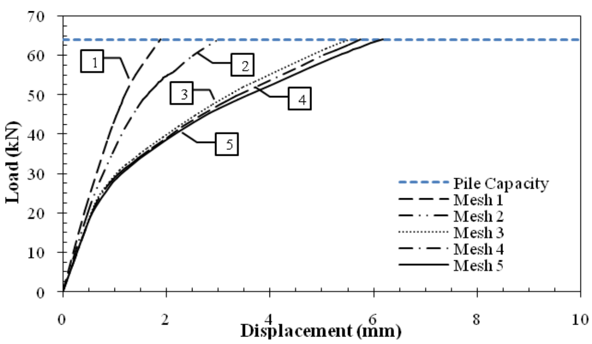

Figure 3. Results of the different FE meshes

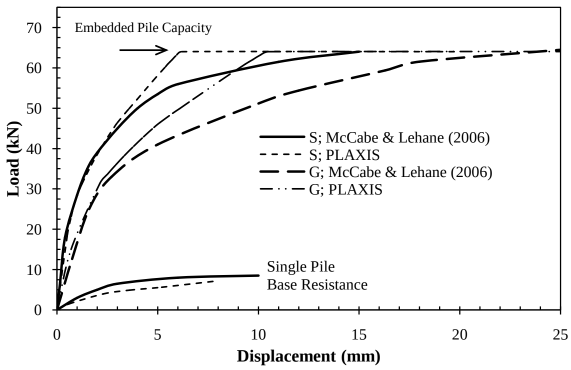

Figure 4. Predictions of single pile and pile group response using embedded piles compared to field data

3.2. Two-pile interaction factors

The present (HS) model has also been employed to compare predictions of two-pile interaction factors determined using embedded pile in PLAXIS to a range of field data and existing predictions; the results of the analyses have been plotted in the traditional form of α against *S/D* in Figure 5. The variation in predictions of α with load level determined by PLAXIS is captured by the shaded region in Figure 5 where the upper and lower bounds represents a load level corresponding to a FOS on single pile capacity of 1.5 and 4, respectively where the pile capacity was defined nominally at a pile head displacement of 10% of the pile diameter, *D*. Although comparisons with the data reported by Cooke (1974) and Caputo and Viggiani (1984) are only indicative (since different soil and pile properties as well as load levels will lead to differences in interaction factors), PLAXIS results show good agreement to the measured field data beyond a value of S/D_{eq}=2.5 (where the equivalent pile diameter $D_{eq}=2B/\pi^{0.5}$). More importantly, the agreement between PLAXIS predictions and the measured data at the Belfast test site show significant agreement.

From Figure 5, it can also be seen that predictions determined by the present analyses and the 2-D nonlinear FE analyses documented by Jardine et al. (1986) show much improved agreement to field data than the predictions determined using the *PIGLET* computer program (Randolph 2003) and the approach documented by Chen et al. (2011) where the soil is idealised as a Linear Elastic (LE) medium. The method employed by Chen et al. (2011) differs from conventional approaches in that a more rigorous approach to consider pile-soil interaction is proposed using the fictitious pile-extended half-space model.

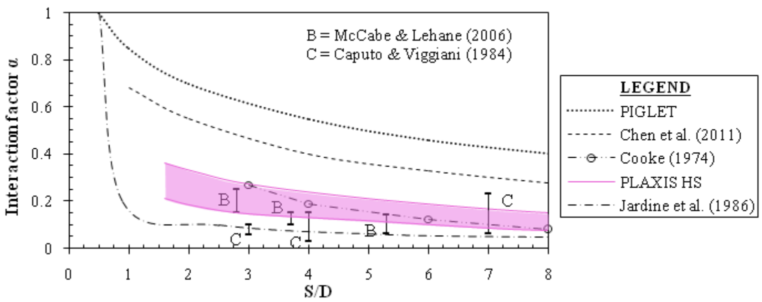

Figure 5. Comparison of interaction factor predictions to field data

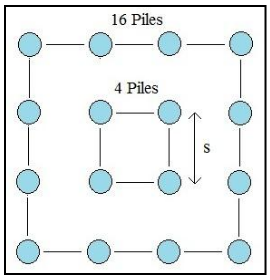

Figure 6. Adopted pile group formation

3.3. Stiffness efficiency of rigidly-capped pile groups

When considering the serviceability of groups of closely-spaced piles, the stiffness efficiency (η_g) term is a useful gauge of the extent of pile-to-pile interaction within the group under working conditions. The value of ηg is defined as follows by Butterfield and Douglas (1981):

$$\eta_g = \frac{k_g}{Nk_s} \qquad (2)$$

where k_g is the stiffness of the pile group, k_s is the stiffness of an equivalent single pile and *N* is the number of piles in the group.

Predictions of η_g of rigidly-capped pile groups determined using embedded piles in PLAXIS is considered in this section using the present soil model. Although it is recognised that nonlinear pile interaction factors (and thus η_g) vary with load level (Sheil and McCabe 2012b), a commonly employed FOS of 2.5 was adopted. The authors also adopted the conventional square pile group formation as the basis of the study, with larger groups developed by placing an extra square of piles around the centre pile as shown in Figure 6.

Both the HS model and a LE soil model in PLAXIS have been used to compare predictions of η_g determined using embedded piles to predictions obtained from existing empirical approaches and charts illustrated in Figure 7. The soil properties adopted in the LE soil model are similar to those employed in the HS model documented by Sheil and McCabe (2012), however soil strength and the stress dependency of soil stiffness are not taken into account. In addition, a constant soil stiffness profile with depth has been employed in the LE analyses in contrast to the 'Gibson' soil profile predicted by the HS model.

A database of stiffness efficiency field data (from six published pile group case histories) provided by McCabe and Lehane (2006) is also included in Figure 7 which is described by the following expression:

$$\eta_g = \frac{\left(D_g \big/ D\right)^{0.66}}{N} \qquad (3)$$

where D_g = equivalent diameter of the plan area of the pile group; D = diameter of the pile (or equivalent diameter for a square pile) and N = the number of piles in the group. The ratio D_g/D is a convenient composite term which captures variations in both pile diameter and spacing. The empirical approach proposed by Fleming et al. (2009), derived from results using PIGLET, was defined as follows:

$$\eta_g \approx N^{-e} \qquad (4)$$

where the exponent, e, typically ranged between 0.5 and 0.6 (a value of e = 0.55 has been adopted in Figure 7). Castelli and Maugeri (2002) recognised the importance of considering soil nonlinearity and thus used hyperbolic load transfer functions to model a more realistic nonlinear pile-soil-pile interaction defined as:

$$\eta_g = \left(\frac{D}{D_g}\right)^{0.15} \qquad (5)$$

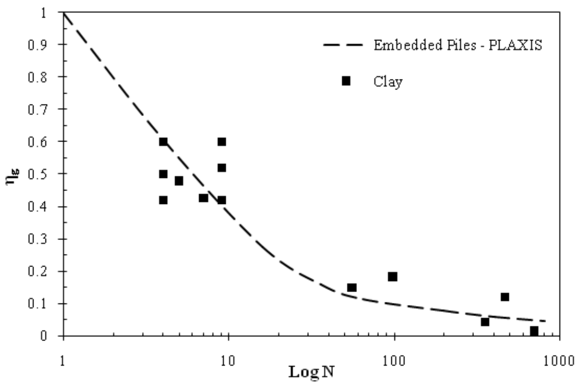

Figure 8. Comparison of stiffness efficiency predictions to field data

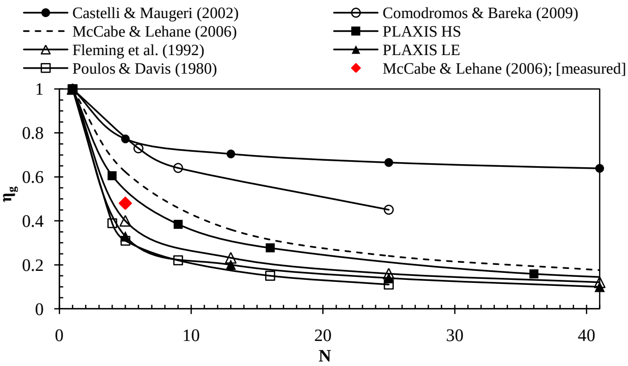

Figure 7. Comparison of present predictions of η_g to existing predictions

From the results presented in Figure 7, the authors have arrived at the following conclusions:

(i) Predictions of η_g using embedded piles with a LE soil model in PLAXIS appear to agree well with existing approaches idealising the soil as a LE medium (Fleming et al. 2009; Poulos and Davis 1980). It is clear, however, that the empirical approach by Fleming et al. (2009) and the charts by Poulos and Davis (1980), using the computer program *PIGLET* (Randolph 2003), under-predict the value of η_g as a consequence of assuming a LE soil medium when compared to field data.

(ii) Predictions of η_g documented by Comodromos and Bareka (2009), using the finite difference code FLAC3D (Itasca Consulting Group Inc 2000), and Castelli and Maugeri (2002) appear to be significantly greater than field data. The values of η_g reported by Comodromos and Bareka (2009) relate to a FOS of 1 (i.e. 0.1D) thus contributing to the over-prediction of η_g in Figure 7. The exponent of 0.15 in the approach documented by Castelli and Maugeri (2002) was derived from a database of case histories, of which not all were friction pile groups. Thus the over-prediction of η_g compared to field data for this approach may be attributed to the influence of end-bearing pile groups in the database.

(iii) PLAXIS results using the embedded piles with the HS model appear to show good agreement with both the η_g of the load test carried out by McCabe & Lehane (2006) in Belfast and the field data documented by the same authors. The higher, more realistic predictions of η_g provided by the HS model compared to LE predictions can be attributed to both the nonlinearity of soil behaviour and the 'Gibson' soil stiffness profile predicted by the HS model. Moreover, the HS model in PLAXIS can be considered as a marked improvement on existing approaches for the prediction of ηg for rigidly-capped pile groups.

In Figure 8, predictions of η_g determined using embedded piles with the HS model in PLAXIS have also been compared to the database of 18 friction pile group case histories in clay presented in Table 2. It can be seen that the embedded piles together with the HS model appear to predict the trend in η_g with increasing group size, *N*, reasonably well when compared to field data. More importantly, however, predictions of η_g show good agreement to measured values for large group sizes and can be considered as a sufficiently accurate method for the prediction of the settlement response of large friction pile groups in clay.

Table 2. Database of measured values of η_g.

Reference	Soil Conditions	Pile Type	N	S/D	L/D	E_B/E_S	h/L	η_{meas}
McCabe & Lehane (2006)	Soft organic clayey silt	Driven concrete	5	2.5	21	-	1.4	0.48
Tejchman et al. (2001)	Sand	Driven concrete	264	3.5	27	-	-	0.066
Tejchman et al. (2001)	Medium sand	Driven concrete	72	4.5	44	-	-	0.311
Tejchman et al. (2001)	Medium sand	Bored concrete	292	5.4	26.5	5	-	0.164
Goosens and Van Impe (1991)	Medium stiff clay	DCIS concrete	697	4	26	-	-	0.017
Briaud et al. (1989)	Medium dense sand	Driven steel	5	3	33.5	-	-	0.6
Thorburn et al. (1983)	Soft very silty clay	Driven concrete	55	7.1	27	-	-	0.15
Thorburn et al. (1983)	Soft very silty clay	Driven concrete	97	7.1	107	-	-	0.184
Bartolomey et al. (1981)	Soft plastic clay	-	464	4.1	32	-	-	0.122
Bartolomey et al. (1981)	Tough plastic clay	Bored	9	3	39	-	-	0.6
Cooke et al. (1981)	London clay	Cast-in-situ	351	3.5	29	-	-	0.044
Trofimenkov (1977)	Stiff silty clay	Driven concrete	7	6	14	-	-	0.426
Trofimenkov (1977)	Stiff silty clay	Driven concrete	9	3	30	-	-	0.52
Koerner & Partos (1974)	Medium dense sand	Driven concrete	132	6.9	19	5	2.3	0.1
Brand et al. (1972)	Soft sensitive marine clay	Driven timber	4	3	40	5	1.4	0.5
Brand et al. (1972)	Soft sensitive marine clay	Driven timber	4	2.5	40	5	1.4	0.6
Brand et al. (1972)	Soft sensitive marine clay	Driven timber	4	2	40	5	1.4	0.4
Koizumi & Ito (1967)	Organic silty clay	Driven steel	9	3	19	2	2.2	0.42

4 CONCLUSIONS

A numerical study on the suitability of embedded piles for the prediction of both single pile and pile group behaviour has been presented using both a linear elastic soil model and the advanced nonlinear Hardening Soil model in PLAXIS 3-D Foundation. The following conclusions arise from the study:

(i) Although pile installation is not explicitly considered and pile bearing capacity is considered as an input parameter with embedded piles, predictions of the load-displacement behaviour of a single pile and 5-pile group load test in soft clay show good agreement to measured data documented by McCabe and Lehane (2006).

(ii) Predictions of two-pile interaction factors using embedded piles together with the HS model agree well to the field data reported by McCabe and Lehane (2006) and can be considered a significant improvement on existing approaches that idealise the soil as a LE soil medium.

(iii) Although the adopted parameters in the present paper are representative of soft clay, predictions of η_g obtained using the present empirical approach show good agreement to a database of field data for a range of clay types. More importantly, however, the HS model together with embedded piles in PLAXIS appears to predict the settlement response of large pile groups with good agreement to field data.

(iv) This paper highlights the ability of embedded piles using beam elements to predict single pile and pile group response with reasonable accuracy. The reduced number of elements in the FE model associated with embedded piles has the potential to alleviate the computing restrictions often associated with 3-D FE analyses thus allowing greater group sizes to be considered where groups of almost 1000 piles were considered in the present study.

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