Three-Dimensional Investigation of Wave-Pile Group Interaction

Using the Scaled Boundary Finite Element Method

Part II: Application Results

Miao Li^{a,*}, Hong Guan^a, Hong Zhang^a and Jun Liu^b

^a Griffith School of Engineering, Griffith University, *QLD*, 4222, Australia

^b Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian, 116024, China

*Corresponding author. Tel: +61 7 555 27608. Email address: m.li@griffith.edu.au

ABSTRACT

This paper is the second part of the study on three-dimensional wave-pile group interaction analysis using the Scaled Boundary Finite Element Method (SBFEM). The verified SBFEM model is employed to investigate wave interaction with pile group foundations. The leading pile experiences greater wave forces and larger displacement magnitudes than other piles. Parametric analyses in terms of wave properties and structural layouts are carried out. Compared with the pile distance, the wave number is a dominant factor affecting wave and structural behaviours. This study is expected to provide valuable information for the design of pile group foundations.

KEY WORDS: wave-pile group interaction; diffraction; structural behaviour; scaled boundary finite element method; three dimensions

1. INTRODUCTION

One predominant foundation concept extensively used in ocean installations is identified as circular cross-sectional structures, appearing as single standing piles for offshore wind turbines, or pile groups supporting various offshore platforms. This naturally leads to the

question of wave interaction with pile group foundations, which differs significantly from wave interaction with single pile foundations. A computational model based on SBFEM has been developed to address this problem, with the theoretical aspects fully detailed in Part I of this study [1]. The model has been verified with satisfactory performance: (1) accurately captures the boundary condition at infinity for the unbounded wave domain; (2) effectively addresses the discussed problem in three dimensions however with released computational burden; (3) successfully integrates a scalar field in which the wave diffraction problem is specified and a vector field where the structural behaviour is investigated.

In this paper, i.e. Part II of the study, the verified SBFEM model is first employed to investigate wave interaction with a group of two piles, with the intention to provide enlightening information when more piles or complex structures are involved. The wave field behaviour is studied followed by subsequent examinations of the piles' responses. A comparison between wave interaction with a group of two piles and that of a single pile is performed, to explore the benefit of pile group foundations. Parametric effects, in terms of wave number, incident wave angle, and the dimension ratio between pile distance and pile radius, are systematically analysed for a thorough understanding of the wave-pile group interaction phenomenon. The verified model is also utilised in a case in which waves interact with a group of three piles to demonstrate the general application of the proposed model. It is expected that the information obtained from this study provide valuable information to academics and engineers in the subject of wave-structure interaction in ocean environment.

2. SBFEM MODEL OF WAVE INTERACTION WITH TWO PILES

A geometric sketch illustrating a group of two piles engaged in ocean environment is shown by an xz plane view and an xy plane view in Fig. 1. The Cartesian coordinate

system is originated at the seabed level with the xy plane laying on the seabed surface and the z axis extending positively upwards. The two piles, denoted by P1 and P2, are of identical radius $a = 0.5$ m. They are seated on the x axis and are placed symmetrically with respect to the y axis. The net distance between the two piles ' d_{Net} ' equals three times the pile radius a . Other parameters reserve the same physical meaning as explained in Table 1 in [1].

The SBFEM model for the wave field is constructed in the xy plane by introducing an auxiliary circular envelop with an radius of $R = 8a$, resulting in an unbounded domain S_∞ and a bounded domain S_b . As illustrated in Fig. 2, S_b is further divided into six bounded subdomains S_i ($i = 1, 2, \dots, 6$) with the scaling centre of each subdomain located at the geometric centre of the subdomain. The scaling centre of the unbounded domain S_∞ is positioned at the centre of the envelope. The circular envelope, the circumferences of the two piles, and the interfaces between adjacent subdomains are discretised using quadratic three-node curvilinear elements.

The SBFEM meshing of the pile foundation are performed three dimensionally. Using a single pile as an illustration, five subdomains are designed for a relatively well-balanced geometric dimension for each subdomain. Accordingly, the entire surface, as well as the interfaces between adjacent subdomains is discretised using eight-node quadratic quadrilateral elements.

3. WAVES INTERACTION WITH TWO PILES

With the specified wave parameters, the wave field behaviour is calculated and the normalised free surface elevation $|\eta_\theta|/A$ is plotted in Fig. 3 for a finite region of the infinite wave domain. An obvious curvature of the wave crests and troughs is perceived, indicating a change in the propagation direction as waves approach the piles. The local enlargement of $|\eta_\theta|/A$ provides information that $|\eta_\theta|/A$ in the vicinity of P1 is generally

greater than that of P2 under the prescribed wave conditions.

A clearer examination of $|\eta_\theta|/A$ distribution around pile circumferences is obtained from Fig. 4. A symmetric pattern of the distribution with respect to the x axis is observed due to the symmetric definition of the problem. It is noticed that, with other conditions being identical, $|\eta_\theta|/A$ around P1 circumference is overall greater than that around P2. At the same time, the difference of $|\eta_\theta|/A$ at the two sides of the piles, the upstream side where $-\pi \leq \theta \leq -\pi/2 \cup \pi/2 \leq \theta \leq \pi$ and the lee side where $-\pi/2 \leq \theta \leq 0 \cup 0 \leq \theta \leq \pi/2$, is significantly mitigated after the wave diffraction with P1 occurs.

Demonstrated by Eqs, (55) and (56) in [1], the quantitative relationship between the dynamic wave pressure p and the free surface elevation η_θ at a certain horizontal level is $p = \rho g \eta_\theta$. Therefore, it is reasonable to infer from Fig. 4 that the resultant force acting in the x direction on P1 is greater than the corresponding resultant force on P2, and that in the y direction on both piles is zero. This will consequently result in a greater displacement in the x direction for P1 than that for P2, and zero displacement in the y direction for both piles, as shown by the solid and dotted lines in Fig. 5 (The dash dotted lines in Fig. 5 and Fig. 6 depict displacement components of P, a single pile standing in isolation and subject to the same wave conditions as P1 and P2. The structural behaviour of P will be addressed later when comparing pile group displacements and single pile displacements). Negative displacements at the bottom of both piles in Fig. 5 (a) are found to be associated with the hydrostatic pressure, which reaches its maximum at the pile bottom level when linearly increases with the water depth.

Fig. 6 shows a polar plot of the displacement variation around pile circumferences at the pile head level. Represented by the solid and the dotted lines for P1 and P2 respectively, the x displacements are uniformly distributed around the pile circumferences, with magnitudes of 0.008 mm and 4.765×10^{-4} mm. Due to symmetry, the y displacement

component is zero all around the pile circumferences.

Fig. 5 and Fig. 6 also show the displacement components (denoted by the dash dotted lines) of a single pile P, calculated under the same wave condition, for comparison purposes. It is found that the displacement amplitude of P is smaller than that of P1, and slightly greater than that of P2. The presence of P2 affects the wave field behaviour around P1, accordingly the structural response of P1, and vice versa. This mutual influence between individual piles in the pile group results in their structural behaviour different from that of piles standing in isolation. The displacement comparison implies that the leading pile, to which waves approach first, experiences a greater resultant wave force than the other pile, and the force is also greater than what the pile would experience in an isolated situation. The other pile, however, with which waves interact afterwards, is subjected to a relatively mild external force compared with the leading pile. It also experiences a milder wave force than it would do if it were standing alone. This contributes to the outperformance of pile groups over single pile foundations in the respect that with randomly generated incident waves from different directions, each pile in the pile group alternately acts against the wave force first, while at the same time keeping other piles sheltered. Therefore, no particular pile will have to consistently withstand extreme wave forces, as is the case with a single pile foundation. This positively prolongs the lifespan and ensures reliable service of pile groups.

4. PARAMETRIC ANALYSIS UNDER VARYING INCIDENT WAVE ANGLE

The parametric analysis performed in [2] provides a clear picture regarding the influence of the parametric variation, in terms of the wave number, wave amplitude and the water depth, on the structural behaviour of a single pile foundation. For wave interaction with pile groups, other parameters, such as the incident wave angle and the dimension ratio between the pile distance and the pile radius are of more significance. Considering the

geometric layout of the two piles, the incident wave angle varies within a range of $[0, \pi/2]$ and is specified as $0, \pi/4$ and $\pi/2$, corresponding to three situations in which the waves incident from a direction in parallel, oblique and orthogonal to the connecting line between the two piles, as illustrated in Fig. 7. The dimension ratio between the pile distance and the pile radius, abbreviated as the dimension ratio in the following text for brevity and denoted as e , is arranged to vary from 1 to 5 with an increment of 1. The wave number is still considered as an important factor affecting both the wave field behaviour and the subsequent structural response. From relevant wave information and the dispersion equation, the wave number is calculated to change from 0.05 m^{-1} to 0.15 m^{-1} by an increment of 0.025 m^{-1} . Table 1 lists the variation of the three parameters, which will be employed in the subsequent discussions.

The parametric analysis is sectioned into three parts according to the prescription of the incident wave angle shown in Table 1. In each case, discussions are focused on how the variation of individual parameters, i.e. the wave number k and the dimension ratio e , and the combination of k and e affect the wave field behaviour and the structural response. The parametric analysis is expected to provide valuable information, which will shed light on the subject of wave-structure interaction.

4.1. Incident wave angle $\alpha = 0$

Fig. 8 depicts the variation of $|\eta_\theta|/A$ around pile circumferences for varying wave number k when $e = 3$ and $\alpha = 0$. In each of the subplots, the solid lines depict the $|\eta_\theta|/A$ distribution for $k = 0.05 \text{ m}^{-1}$; the dotted lines for $k = 0.075 \text{ m}^{-1}$; the dash dotted lines for $k = 0.10 \text{ m}^{-1}$; the dashed lines for $k = 0.125 \text{ m}^{-1}$ and the solid lines with dotted markers for $k = 0.15 \text{ m}^{-1}$. With $\alpha = 0$, the distribution of $|\eta_\theta|/A$ around pile circumferences present a symmetric pattern with respect to the x axis. Generally, $|\eta_\theta|/A$ around P1 circumference is

greater than that of P2 for corresponding cases. A relatively uniform distribution of $|\eta_\theta|/A$ around pile circumferences is noticed for both piles when the wave number is small. As the wave number increases, $|\eta_\theta|/A$ increases considerably on the upstream side of P1, whereas that on the lee side increases with a small magnitude. Subsequently, an elongated shape is developed with its longer axis in alignment with the incident wave direction as the wave number becomes larger. For P1, the maximum $|\eta_\theta|/A$ always appears at $\theta = \pi$ where the pile first confronts against the incoming waves. The location of the minimum $|\eta_\theta|/A$, however, is visible at where θ is slightly less than $\pi/2$ with mild shifts when k changes. For P2, the maximum $|\eta_\theta|/A$ is found at $\theta = 0$, the lee side of the pile, for relatively small k . It switches to $\theta = \pi$, the upstream side of the pile, when the wave number becomes significant. The minimum $|\eta_\theta|/A$ on P2 circumference varies roughly around $\theta = \pi/2$. It can be inferred that the maximum $|\eta_\theta|/A$ on the pile circumference always appears in the incident wave direction, and the minimum $|\eta_\theta|/A$ can be approximately found in its orthogonal direction.

Following the discussion of the location of $|\eta_\theta|/A$ extrema around pile circumferences, a corresponding examination of the magnitude variation is carried out. The magnitude variation of $|\eta_\theta|/A$ is not solely related to any single parameter, i.e. the wave number k or the dimension ratio e . It is a multivariate function of both parameters. Thus, Fig. 9 is drawn to identify the interrelationship between the combination of the two parameters and the extrema. As shown in subplot (a), the maximum $|\eta_\theta|/A$ on P1 circumference increases and the increase becomes more noticeable as the value of k rises, especially with a greater e . Examining the subplot for each individual k , denoted by the same markers on different lines ('+' for $k = 0.05 \text{ m}^{-1}$, 'o' for $k = 0.075 \text{ m}^{-1}$, '∇' for $k = 0.10 \text{ m}^{-1}$, '□' for $k = 0.125 \text{ m}^{-1}$ and '◇' for $k = 0.15 \text{ m}^{-1}$), it is found that for any specific k , the maximum increases when e goes up. However, this increase is rather mild for small k . It becomes remarkable when k becomes greater but with a slight downgrade in the increase

with respect to e as shown by ‘ $\diamond$ ’ in the plot.

Fig. 9 (b) and (c) provide similar variation pattern of the maximum $|\eta_0|/A$ for P2 and the minimum $|\eta_0|/A$ for P1. The extrema decrease first when e is no less than 2 followed by a subsequent rise as k increases, or show a constant decrease when $e = 1$. Analogically, by viewing the subplots for any definite k , an increase in the maximum $|\eta_0|/A$ for P2 or the minimum $|\eta_0|/A$ for P1 is observed as the value of e rises.

The minimum $|\eta_0|/A$ around P2 illustrated in Fig. 9 (d) shows a tendency of decrease with k for any particular e although it increases as the two piles are further away from each other for any certain k .

An overview of Fig. 9 reveals that a greater wave number corresponds to more significant wave diffraction phenomenon in the presence of pile foundations. The variation of the wave number has a considerable influence on the $|\eta_0|/A$ extrema for both piles regardless of the variation of e . The effect of the variation of e , however, is largely related to the magnitude of the wave number. For any value of k , all subplots show an increase in $|\eta_0|/A$ extrema, however the increase becomes less prominent as e increases. This tendency is far more obvious with large wave numbers than that with small ones.

The corresponding pile behaviour in response to the wave forces is studied, with the displacement component of the centre of the pile head plotted in Fig. 10. As the physical problem is symmetric with respect to the x axis when $\alpha = 0$, the displacement component in the y direction is zero, and thus is not presented. Overall, the x displacement component of P1 is greater than that of P2 for corresponding cases. This is due to the fact that the dynamic wave energy associated with the wave motion has been mitigated after the wave diffraction with P1 happens. The x displacement of P1 shows substantial increase with k for any e , but it is noticed that for a specific k , it decreases when e increases. The x displacement of P2, on the other hand, demonstrates a different variation

pattern. The lower part of subplot (b) shows negative displacements, indicating an opposite displacement direction to that of P1 for a combination of small k and e . The magnitude first increases and then goes down when k increases, however, it shows a monotonic decrease as the value of e rises. When e and k become greater at the upper corner, positive displacements are observed and the magnitudes increase with respect to both k and e . Once again, the influence of the variation in dimension ratio e on the pile displacement only becomes prominent when the wave number is large, and the degree of influence is steadily degraded as e keeps increasing.

4.2. Incident wave angle $\alpha = \pi/4$

When the incident wave direction is $\pi/4$, small wave number still generates uniform $|\eta_\theta|/A$ distribution around the pile circumferences. As the wave number increases, the magnitudes of $|\eta_\theta|/A$ become greater around where the incident waves first approach the pile. Due to the presence of P2, the location of the maximum $|\eta_\theta|/A$ on P1 circumference moves around $\theta = -3\pi/4$ with a slight shift to the right. The corresponding minimum appears at around $\theta = 2\pi/3$. As far as P2 is concerned, the maximum $|\eta_\theta|/A$ occurs at the left of $\theta = \pi/4$ for relatively small e and k , however, when the net distance between the two piles becomes substantial, the influence of P1's presence on the wave behaviour around P2 is weakened to an extent that the maximum $|\eta_\theta|/A$ switches to $\theta = -3\pi/4$ for $e > 3$ and $k = 0.15 \text{ m}^{-1}$. The minimum $|\eta_\theta|/A$ remains at around $\theta = -\pi/4$ for any combination of e and k . It can be readily concluded that, for both piles, the maximum $|\eta_\theta|/A$ always locates approximately in alignment with the incident wave direction. The minimum, however, is roughly in the perpendicular direction. Fig. 11 shows the $|\eta_\theta|/A$ variation around pile circumferences of the case with $e = 3$ and $\alpha = \pi/4$ for illustration purposes.

The variations of the maximum $|\eta_\theta|/A$ on P1 circumference and the minimum $|\eta_\theta|/A$ on P2 circumference in Fig. 12 show the same tendency as their counterparts when $\alpha = 0$ (see

Fig. 9). The minimum $|\eta_\theta|/A$ on P1 circumference decreases as k increases, but shows a tendency of potential increase with k when e is large enough. The maximum $|\eta_\theta|/A$ on P2 circumference reduces when the wave number k increases, and it is not affected much by the dimension ratio e except when its location shifts abruptly from around $\theta = \pi/4$ to $\theta = -3\pi/4$ when $k = 0.15 \text{ m}^{-1}$ and $e > 3$.

The displacement components in the x direction for both piles demonstrate similar variation pattern with respect to e and k when compared with the corresponding plots in Fig. 10 for $\alpha = 0$, with a slight difference in the magnitudes. As the physical problem is no longer symmetric when $\alpha = \pi/4$, significant displacement in the y direction for both piles are observed and they present similar variation pattern to their x counterparts. Both x and y displacement components of P1 are greater than those of P2, which signifies that the leading pile generates greater displacements. The other pile, however, experiences a relatively gentle wave impact due to the presence of the preceding pile, and consequently presents comparatively moderate displacement.

4.3. Incident wave angle $\alpha = \pi/2$

When the incident wave angle shifts to $\pi/2$, the incident wave direction is orthogonal to the connecting lining between the two piles. The physical problem is symmetric with respect to the y axis, and the two piles are equivalent to each other. Accordingly, the wave field behaviour demonstrates a symmetric pattern. The $|\eta_\theta|/A$ distribution around P1 circumference mirrors that of P2 with respect to the y axis, and vice versa. The maximum $|\eta_\theta|/A$ on both pile circumferences appears at around $\theta = -\pi/2$. The minimum $|\eta_\theta|/A$ can be visible at corresponding symmetric positions on P1 and P2 circumferences, i.e. around $\theta = 0$ for P1 and $\theta = \pi$ for P2.

The maximum and minimum $|\eta_\theta|/A$ on P1 and P2 circumferences show identical variation

pattern with respect to the two parameters, and only the plots for P1 are presented in Fig. 15. The maximum $|\eta_\theta|/A$ first decreases as k increases to 0.075 m^{-1} , followed by a subsequent significant rise when k increases to 0.15 m^{-1} . Unlike the plots in Fig. 9 and Fig. 12, in which the maximum either increases or decreases consistently as the value of e rises for certain k , the maximum $|\eta_\theta|/A$ shown in Fig. 15 first decreases when e goes up from 1 to 3 and then increases when e continues to go up to 5. This indicates that when the incident wave direction is orthogonal to the connecting line of the two piles, the maximum $|\eta_\theta|/A$ on the pile circumference is not a monotonic function of the pile distance, there is a dimension ratio e when the maximum $|\eta_\theta|/A$ falls to a minimum, which equals 3 in the present case. The minimum $|\eta_\theta|/A$, however, displays a simple declining tendency with k , and monotonically increases with a dropping slope when e becomes larger for a certain k .

The variation of the displacement components in both x and y directions are plotted in Fig. 16 to examine the corresponding structural behaviour. Though Fig. 15 presents a non-sequential variation pattern of the maximum $|\eta_\theta|/A$, the displacement components show a sequential variation pattern. Both x and y displacement components increase with k for any definite e , and descend with a reducing slope as e increases for any particular k . Another noteworthy phenomenon is that the displacement component in the y direction is larger than its x counterpart as indicated from the $|\eta_\theta|/A$ distribution in Fig. 14, the resultant force acting on the pile in the y direction is greater than that in the x direction. P2 holds the same magnitude of the displacement in the x direction as P1 but with an opposite sign. The displacement in the y direction is precisely the same as that of P1 in both magnitude and direction.

5. WAVE INTERACTION WITH OTHER PILE GROUP FOUNDATIONS

The previous sections present the wave field behaviour in the presence of two piles and

their corresponding responses, with a view to providing fundamental as well as informative understanding of the interaction phenomenon. This section further testifies the applicability of the SBFEM model to more general cases by investigating wave interaction with other pile group foundations. A group of three cylindrical piles, laid at the three vertices of an equilateral triangle are examined. The top view of the pile group foundation is shown in Fig. 17 (a), with the three cylindrical piles denoted as P1, P2 and P3. The three piles have an identical radius of 0.5 m with the net distance d_{Net} being equal to a . Other relevant parameters hold the same magnitudes as those listed in Table 1 in [1]. The corresponding subdomain division of the SBFEM model for wave analysis is illustrated in Fig. 17 (b), and that for the structural analysis for the three piles is the same as shown in Fig. 2 (b).

Considering the spatial layout of the piles, the free surface elevation for an incident wave angle $\alpha = -\pi/2$ is specifically examined. With this specification, P1 is located on the symmetric axis, and P2 and P3 are positioned separately at the two sides of the axis of symmetry. Therefore, the distribution of $|\eta_0|/A$ around P1 circumference is symmetric with respect to the incident wave direction, as can be seen from Fig. 18. $|\eta_0|/A$ is examined to be greater at the upstream side ($0 \leq \theta \leq \pi$) than that on the lee side ($-\pi \leq \theta \leq 0$), with a maximum being 1.0031 at $\theta = \pi/2$ and a minimum being 0.9948 at $\theta = -\pi/2$. The $|\eta_0|/A$ distribution of P2 is symmetric to that of P3 with respect to the incident wave direction with a minimum being 0.9926 at $\theta = 0.04\pi$ for P2 and the same minimum value for P3 but at a corresponding symmetric location where $\theta = 0.96\pi$. The maxima for P2 and P3 are both found at $\theta = -\pi/2$ with a magnitude of 0.9968.

Fig. 19 illustrates the corresponding structural behaviour of three piles when $\alpha = -\pi/2$ and $k = 0.10 \text{ m}^{-1}$. Zero x displacement of P1 is examined in Fig. 19 (a) due to symmetry with respect to the incident wave direction, i.e., the y direction. The x displacements for P2 and

P3 examined at $\theta = 0$ hold the same magnitude of 7.009×10^{-4} mm but with opposite signs. The displacement of P1 in the y direction has a magnitude of 2.42×10^{-2} mm, while those of P2 and P3 are comparatively insignificant and they superimpose with each other as evident in Fig. 19 (b).

A full and systematic parametric study evaluating structural behaviour and wave responses is not detailed herein. It can be performed in the same way as that for wave interaction with two piles. In addition, pile groups with any arbitrary number of piles having either circular or irregular cross-sections can be analysed following the solution procedure presented in Section 3 in Part I [1]. As discussed, the proposed SBFEM-based model is applicable to very general wave-pile group interaction problems.

6. CONCLUSIONS

Together with Part I of this study [1], this part discusses the implementation of a three-dimensional investigation of wave-pile group interaction using SBFEM. The application results of the proposed model are presented. The wave interaction with pile group foundations is studied with important conclusions summarised as follows:

- Symmetric problem configuration leads to symmetric wave field behaviour and accordingly, symmetric structural response of the piles.
- Small wave numbers correspond to relatively uniform $|\eta_\theta|/A$ distribution around pile circumferences, indicating insignificant resultant wave forces acting on piles, thus moderate pile displacements.
- Greater wave numbers render the $|\eta_\theta|/A$ distribution around pile circumferences an elongated shape with its longer axis approximately oriented in the incident wave direction, where the maximum $|\eta_\theta|/A$ is located. The minimum, however, is roughly visible at the perpendicular direction.
- The difference of $|\eta_\theta|/A$ at the upstream side and the lee side is greater for the

leading pile, to which waves approach first, implying greater resultant wave force and consequently larger displacement of the leading pile than those of succeeding piles. With randomly generated wave forces, each pile in the pile group serves alternately as the leading pile, dissipating a portion of the mechanical energy associated with the wave motion, therefore contributing to a longer lifespan of the pile group.

- The wave number has considerable influence on $|\eta_0|/A$ distribution and also the pile behaviour no matter what the pile distance is. The effect of the dimension ratio e on the wave field and the pile behaviour, however, largely depends on the magnitude of the wave number. The physical quantity ($|\eta_0|/A$ or displacement), either increasing or decreasing with respect to e , displays more obvious variation tendency with a large wave number than that with a small one.

It is worth mentioning that the SBFEM model proposed in this study is applicable for investigations of wave interaction with any arbitrary number of piles of various cross-sections and spatial layouts. Future analysis, focusing on the time-dependent structural behaviour of the pile groups, will be conducted to gain additional insight into the physical nature of the problem.

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Fig. 1. Geometric model of a group of two piles in ocean environment: (a) xz plane view and (b) xy plane view

Fig. 2. SBFEM model for (a) wave field analysis and (b) structural analysis

Fig. 3. $|\eta_\theta|/A$ of a finite region with a local magnification for wave diffraction with two piles when $k = 0.10 \text{ m}^{-1}$ and $\alpha = 0$

Fig. 4. $|\eta_\theta|/A$ around pile circumferences when $k = 0.10 \text{ m}^{-1}$ and $\alpha = 0$

(a)

(b)

Fig. 5. Displacement components along pile height at $\theta = 0$ with $k = 0.10 \text{ m}^{-1}$ and $\alpha = 0$ (a) in the x direction and (b) in the y direction

(a)

(b)

Fig. 6. Displacement components around pile circumferences at pile head level with $k =$

0.10 m^{-1} and $\alpha = 0$: (a) in the x direction and (b) in the y direction

Fig. 7. Variation of the incident wave direction

Fig. 8. $|\eta_\theta|/A$ around pile circumferences for varying k when $e = 3$ and $\alpha = 0$ for: (a) P1 and (b) P2

(a)

(b)

(c)

(d)

Fig. 9. Variation of $|\eta_\theta|/A$ extrema with k for varying e when $\alpha = 0$ for: (a) maximum for P1; (b) maximum for P2; (c) minimum for P1 and (d) minimum for P2

Fig. 10. Variation of displacement with k for varying e when $\alpha = 0$ for: (a) P1 and (b) P2

Fig. 11. $|\eta_\theta|/A$ distribution around pile circumferences for varying k when $e = 3$ and $\alpha = \pi/4$ for: (a) P1 and (b) P2

(a)

(b)

(c)

(d)

Fig. 12. Variation of $|\eta_\theta|/A$ extrema with respect to k and e when $\alpha = \pi/4$ for: (a) maximum for P1; (b) maximum for P2; (c) minimum for P1 and (d) minimum for P2

(a)

(b)

(c)

(d)

Fig. 13. Variation of displacement extrema with respect to k and e when $\alpha = \pi/4$ for: (a) maximum u_x for P1; (b) maximum u_x for P2; (c) maximum u_y for P1 and (d) maximum u_y for P2

Fig. 14. $|\eta_0|/A$ distribution around pile circumferences for varying k when $e = 3$ and $\alpha = \pi/2$ for: (a) P1 and (b) P2

Fig. 15. Variation of $|\eta_0|/A$ extrema with respect to k and e when $\alpha = \pi/2$: (a) maximum and (b) minimum

Fig. 16. Variation of displacement with respect to k and e when $\alpha = \pi/2$ for P1: (a) maximum and (b) minimum

Fig. 17. Top view of three cylindrical piles with an auxiliary envelope: (a) geometric layout and (b) SBFEM model for wave field analysis

Fig. 18. $|\eta_0|/A$ around pile circumferences for $k = 0.10 \text{ m}^{-1}$ and $\alpha = -\pi/2$

Fig. 19. Displacement components along pile height at $\theta = 0$ with $k = 0.10 \text{ m}^{-1}$ and $\alpha = -\pi/2$: (a) in the x direction and (b) in the y direction

Table 1. Parameter variation specification for parametric analysis

Parameters	Magnitudes				
Wave number k (m^{-1})	0.05	0.075	0.10	0.125	0.15
Dimension ratio $e = d_{Ne}/a$	1	2	3	4	5
Incident wave direction α (rad)	0	$\pi/4$	$\pi/2$	-	-