Proceedings of the 6th International Conference on the Application of Physical Modelling in Coastal and Port Engineering and Science (Coastlab16)

Ottawa, Canada, May 10-13, 2016

INTERACTION OF WAVES AND VERTICAL ARRAY OF SLENDER PILES

LISHAM BONAKDAR[1] & HOCINE OUMERACI[2]

1 Leichtweiß-Institute for Hydraulic Engineering and Water Resources (LWI), Technische Universität Braunschweig Beethovenstrasse 51a, 38106 Braunschweig Germany, l.bonakdar@tu-braunschweig.de

2 Leichtweiß-Institute for Hydraulic Engineering and Water Resources (LWI), Technische Universität Braunschweig Beethovenstrasse 51a, 38106 Braunschweig Germany, h.oumeraci@tu-braunschweig.de

ABSTRACT

Pile group effect on the wave loading of a slender pile is investigated by means of small scale experiments performed in 2 m-wide wave flume of Leichtweiss-Institute for Hydraulic Engineering and Water Resources (LWI) in Braunschweig, Germany. Different pile arrangements including single, side by side, tandem, 2×2 and staggered with relative spacing of S_G/D=0.5 – 5 were tested. For all pile configurations, *KC* number varied from 1.1 to 88 meaning that all wave-induced flow regimes were covered. The focus in this paper is put on the influence of different hydrodynamic and structure parameters on the wave loading of a slender pile within further neighbouring piles in side by side arrangement.

KEWORDS: Slender pile, Side by Side arrangement, KC number, Relative spacing parameter, Pile group effect

1 INTRODUCTION

There might be a common assumption that two or more piles in a flow should have a similar behaviour to that of a single isolated pile, but this assumption is correct only when they are adequately apart (Zdravkovich, 1977). For closely-spaced piles in groups in waves, which can be commonly found in offshore and coastal environments (Figure 1), the interference effects between piles may significantly change the flow around the piles, and thus the wave load as compared to that on a single isolated pile. In such structures, wave load on a single slender pile is significantly affected by the neighbouring piles and can thus not be calculated by the commonly applied formula of Morison et al. (1950).

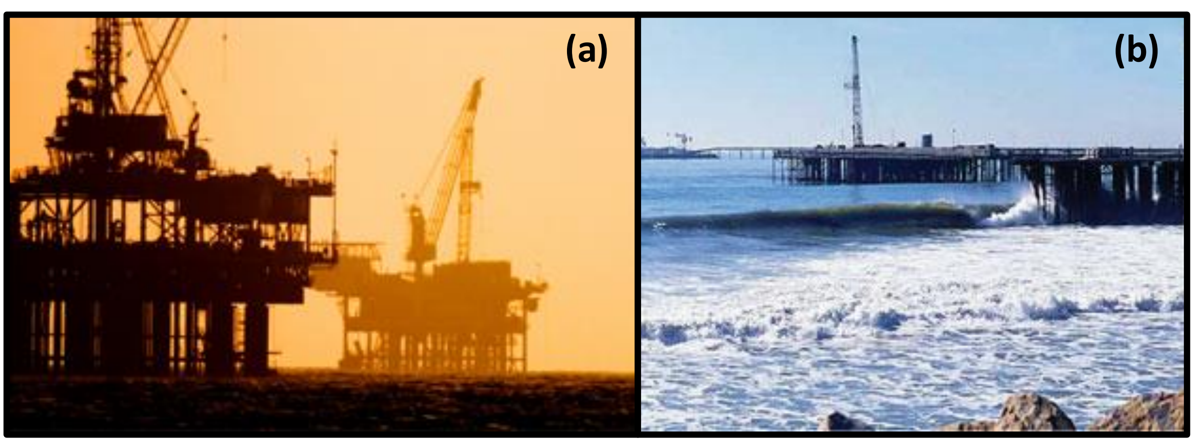


Figure 1. Pile group-supported a) offshore platform b) coastal pier structure (www.gasdetection.com)

Given the high complexity of the interaction between waves and pile groups in different arrangements, laboratory experiments still represent the most reliable alternative. A number of experimental studies have been carried out to investigate the interference effects of the adjacent piles. The methods of experimental studies used to predict wave loads on pile group can be chiefly classified in two main categories: "Wave force coefficient approach" and "Wave force approach".

In the wave force coefficient approach, the inertia and drag coefficients are determined by minimizing the differences between the estimated and measured wave force when both velocity and acceleration are known. This approach was used for instance by Chakrabarti (1981; 1982) and Smith and Haritos (1997). Using the calculated drag and inertia coefficients, Chakrabarti (1981; 1982) computed maximum wave forces and compared them to measured forces. Smith and Haritos (1997) reported that drag and inertia coefficients are dependent on the Keulegan–Carpenter (KC) number ($KC=u_{max}T/D$) and relative spacing S_G/D where u_{max} is the maximum horizontal wave-induced flow velocity, T is wave period, D is pile diameter and S_G is the gap between the surfaces of two neighbouring piles in a group of piles. Drag and inertia coefficients were usually plotted versus KC number for different relative spacing S_G/D in these studies. However, the proposed C_D and C_M values were noticeably scattered demonstrating that different C_D and C_M values can be obtained for a given KC number.

In the wave force approach, the ratio of wave force on a pile within a group and that on a single isolated pile is determined. This method was applied by Mindao et al. (1987) and Li et al. (1993). Li et al. (1993) stated that the wave-induced force on a slender pile within a group of piles depends on the KC number and relative spacing S_G/D. Mindao et al. (1987) introduced two parameters named *interference coefficient* K_g and *shelter coefficient* K_z for side by side arrangement and tandem arrangement, respectively. Both K_g and K_z coefficients are representative for the force ratio (F_{Group}/F_{Single}) where F_{Group} is the wave force on a slender pile within further neighbouring piles and F_{Single} is the wave force on a single isolated pile. They stated that S_G/D is the most significant parameter and proposed the two following formulae for the estimation of interference coefficient K_g and shelter coefficient K_z for side by side arrangement and tandem arrangement, respectively:

$$K_g = 1.265 - 0.225 Ln\left(S_G/D\right) \qquad \text{for side-by-side} \qquad (1)$$

$$K_z = 0.836 + 0.141 Ln\left(S_G/D\right) \qquad \text{for tandem} \qquad (2)$$

In the proposed formulae, the wave parameters have no influence on the interference K_g and shelter K_z coefficients. The latter are only dependent on the pile group arrangement and relative spacing parameter S_G/D, which was varied from 0.5 to 3.0 in the laboratory tests. Li et al. (1993) introduced *significant pile group effect* $K_{G1/3}$ for piles in side by side arrangement exposed to irregular waves. They found out that the maximum $K_{G1/3}$ occurs when KC number is between 15 and 20 for the case of pure waves. They also showed that, for a given pile group configuration, the combination of wave and current results in smaller grouping effect compared to pure wave condition. For shallow water conditions, Kudeih et al. (2010) performed an experimental study on the wave-induced as well as wave and current-induced forces on three piles in an array. They stated that wave load values on the instrumented pile group are significantly affected by the gap size.

2 RESEARCH STUDY ON WAVE-PILE GROUP INTERACTION AT LWI

Despite the fact that the available experimental studies have contributed to enhance the knowledge about the interaction between wave loads and pile groups, several knowledge gaps and model weaknesses still remain which should be overcome to achieve a safe design of pile-supported marine structures. A research project entitled "Breaking and Non-Breaking Wave Load on Pile Group-Supported Marine Structures" (WaPiGS) is currently being conducted at Leichtweiss-Institute (LWI) to improve the understanding of processes associated with the interaction of breaking/non-breaking waves and pile groups. The objectives of this research project are (i) the generation of a knowledge base for a better understanding of the physical processes involved in the interaction of waves and pile groups considering the effects of the most relevant influencing parameters which include different hydrodynamic and structural conditions, and (ii) the development of more physically-based and more generic formulae for the prediction of wave loads on a slender pile within a pile group as a function of the most influencing hydrodynamic and structural parameters.

The research methodology, applied to achieve the objectives, comprises five distinct work packages (WP 1 - WP 5) related to laboratory experiments, numerical modelling and data analysis as summarized in Figure 2. As shown in Figure 2, (i) a number of large-scale model tests performed in the Large Wave Flume (GWK) in Hannover, Germany, are analysed (Bonakdar and Oumeraci, 2012); (ii) new wave flume experiments are performed in two phases in a smaller scale in the wave flume of Leichtweiss-Institute (LWI) in Braunschweig, Germany. In phase 1, the difference between Froude scaled wave loads obtained in the 6.5 larger scale model tests (GWK) and those measured in LWI for the case of single pile due to scale and model effects is not of great relevance for the prediction of pile group effect K_G. In fact, it was shown that pile group effect K_G values obtained from LWI and GWK tests are similar for a given structural and hydrodynamic conditions (Bonakdar and Oumeraci, 2014); (iii) a hybrid 2D-3D numerical model is developed to simulate the interaction of waves and pile groups for different pile configurations and wave regimes (El Safti et al., 2014). The developed model is used for further parameter study with the focus on the parameters which were not physically investigated. Finally, a computational tool is developed in order to make a more efficient analysis of all obtained data and to generate wave load formulae for the prediction of wave loads on a slender pile in pile groups with different arrangements (Bonakdar 2014 and Bonakdar et al., 2015). In this paper, however, some key results of Phase 2 of the small scale laboratory tests performed in 2m-wide wave flume of Leichtweiss-Institute (LWI) are discussed with a focus on the results obtained for side by side arrangement.

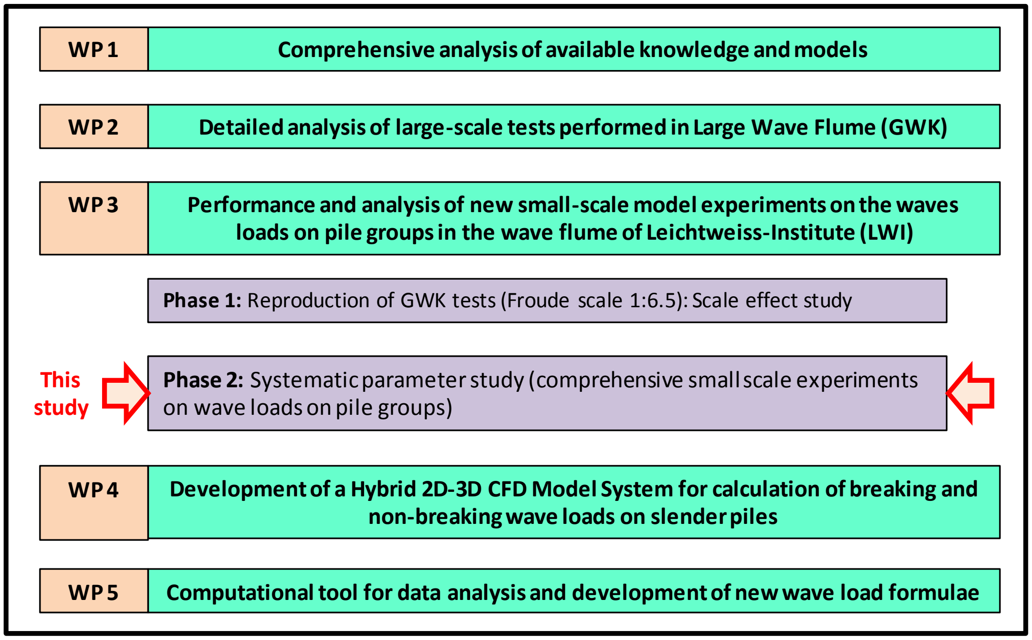


Figure 2. Research methodology of the WaPiGS project

3 LWI LABORATORY TESTS

The plan view and cross section of the model set-up exemplarily for the case of side by side arrangement are drawn in Figures 3 and 4, respectively. As seen, in addition to the pile group and far from it, an isolated single pile was also placed in the wave flume as a reference pile. A distance of 8D was considered between the single isolated pile and the sidewalls of the wave flume to avoid any influence of the walls on the wave loading of the single pile. In order to avoid possible unrealistic flow behaviour at the end of piles, the constructed 1-m long piles were stretched to the bottom of the wave flume with a gap of only a 2-cm between piles and bottom (Figure 4). This very small gap was needed for technical reasons related to the transducers for measuring total force and moment on the slender piles. The wave-induced flow velocity is negligibly small near the bottom of the flume and, therefore, this 2-cm gap does not affect the resulting wave force. Water elevation at the piles and, consequently, wave height at the piles were measured by wave gauges.

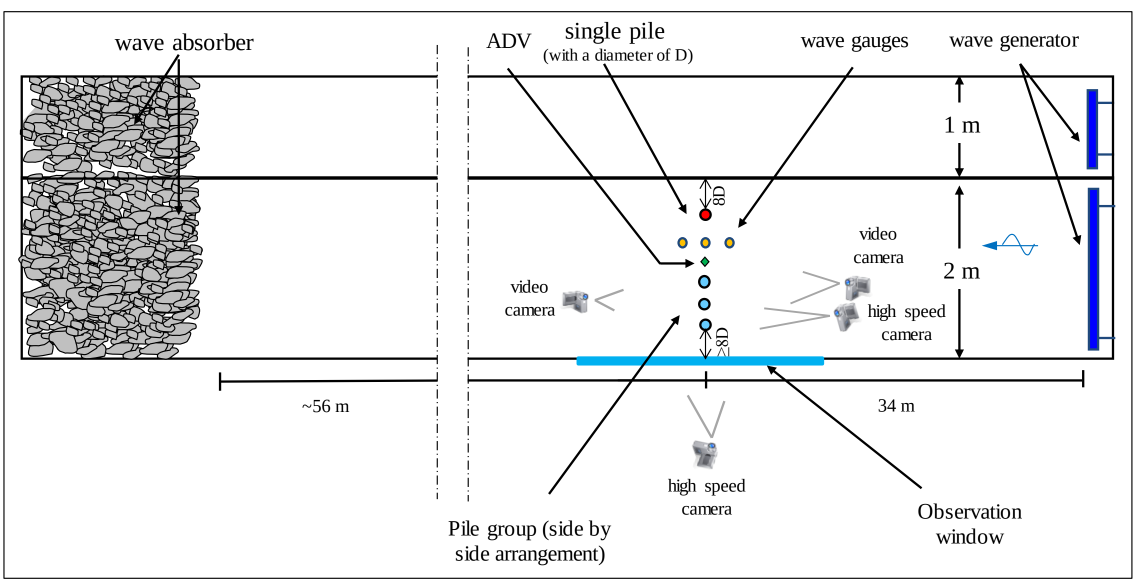


Figure 3. Plan view of model set-up of LWI tests, exemplarily for a pile group with side by side arrangement

As seen in Figure 4, force and moment transducers were placed on the top of the 5 cm diameter piles to measure the total wave force and moment on the instrumented pile. In addition, local wave forces on short pile segments (line forces) were also measured by the so-called ring transducers located at the elevations of 0.14, 0.30 and 0.46 m below SWL. In other words, for each test, the line force was simultaneously measured at three different relative water elevations (z/h = 0.78, 0.53 and 0.28). An Acoustic Doppler Velocimeter (ADV) was installed far from the pile group to measure the undisturbed horizontal wave-induced flow velocity at the elevations of ring transducers. This will allow us to avoid averaging the flow velocity over the depth. The deployment of three ring transducers at different elevations below SWL allows us to examine whether and how the group effect varies over the water depth. The main instrumented pile, which is shown as the middle pile of the side by side arrangement in Figure 4 has three more ring transducers above still water level. These 2.5-cm ring transducers for line forces up to 10 N were designed to measure local impact forces induced by focused waves at different elevations over the entire impact area. The analysis of these measurements is not, however, the focus of this paper.

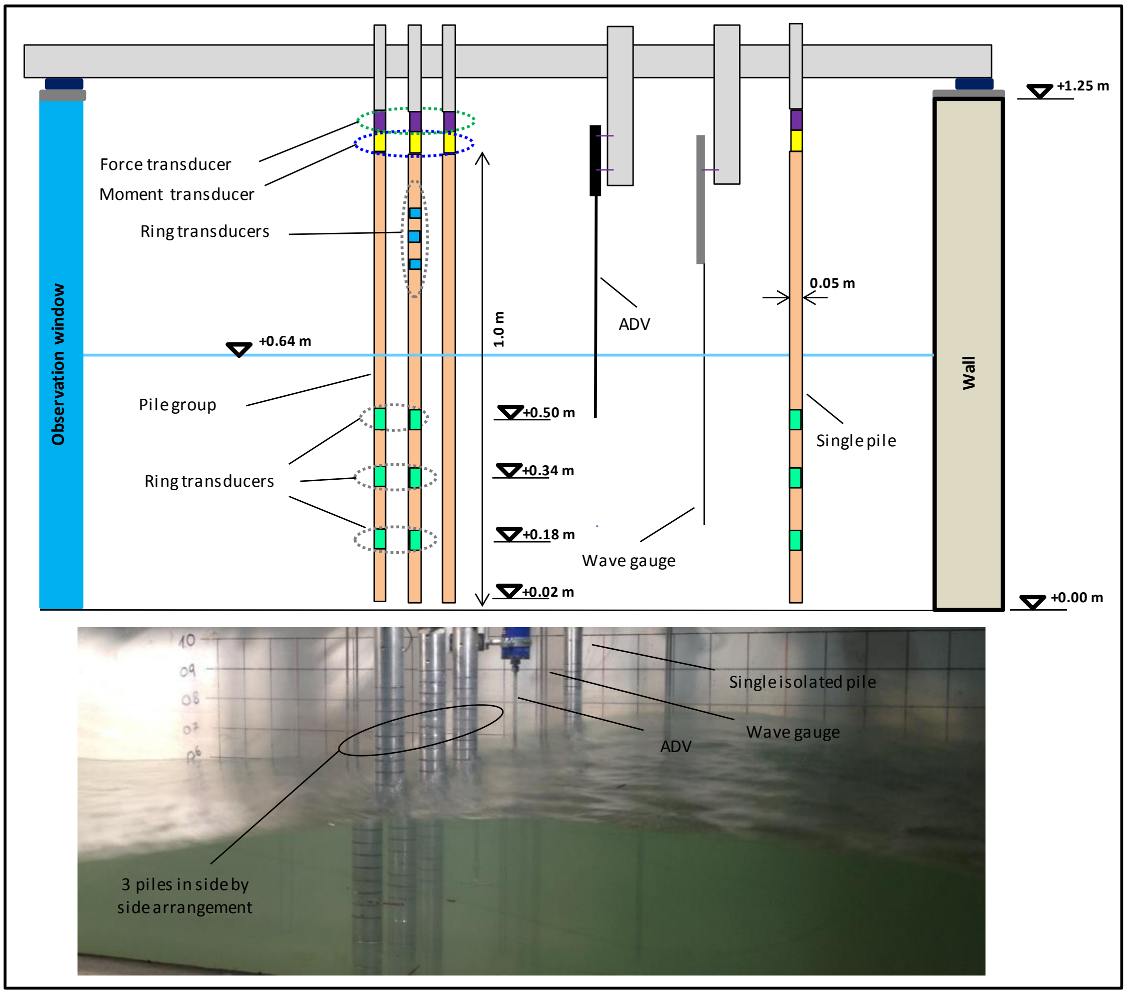


Figure 4. Cross-section and a snapshot of model set-up of LWI tests, exemplarily for a pile group with side by side arrangement

In the LWI tests, in addition to the three basic pile group arrangements, a new pile group arrangement, hereafter named "2×2 arrangement", was also tested which may be considered as a combination of the three basic arrangements side by side, tandem and staggered. Figure 5 shows all 25 configurations tested in the LWI flume. As seen, each pile arrangement was tested for a wide range of relative spacing S_G/D varying from 0.5 where piles are very closely spaced to 5.0 where the piles are so widely spaced that no grouping effect is expected. In this paper, however, only the results obtained for side by side arrangement are discussed.

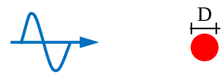
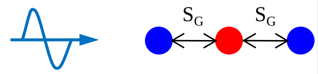
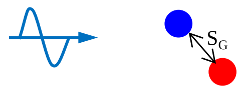
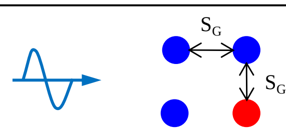
Pile Arrangement		*Relative Spacing (S_G/D)*	*Number of tests*
Single		-------------	24
Tandem		0.5, 0.75, 1, 1.5, 3, 4 and 5	136
Side by side		0.5, 0.75, 1, 1.5, 2, 3 and 5	146
Staggered		0.6, 0.75, 1, 1.5, 3 and 5	120
2 × 2		0.5, 0.75, 1 and 2	83
Instrumented pile (red) Neighbouring pile (blue)			

Figure 5. Pile configurations

For all 25 pile configurations shown in Figure 5, 24 regular non-breaking waves with different wave heights and periods were performed. The ranges of hydrodynamic parameters are given in Table 1. As seen, wave steepness varies from 0.008 to 0.073 which was the maximum possible wave steepness without breaking waves. Relative water depth *h/L* varies from 0.042 to 0.64 meaning that deep, transition and shallow water conditions are covered. The *KC* number changes from 1.1 where inertia regime dominates to 88 where drag regime dominates. Reynolds number varies from $Re = 0.34\times10^4$ to $Re = 3.68\times10^4$ indicating that the LWI model is located in the subcritical zone. Both drag and inertia regimes as well as the transition regime were tested in the LWI experiments, including deep, transition and shallow water conditions.

Table 1. Tested wave conditions

Wave type	Non-breaking regular waves
KC number	1.1 ~ 88.5
Reynolds number	$0.34\times10^4 \sim 3.68\times10^4$
Relative water depth (h/L)	0.042 ~ 0.64
Wave steepness (H/L)	0.008~0.073

4 PILE GROUP EFFECT FOR SIDE BY SIDE ARRANGEMENT

A detailed analysis was made on the effect of non-dimensional wave parameters such as *KC*-number, Reynolds number *Re*, relative water depth *h/L* and wave steepness *H/L* on pile group effect K_G. The latter represents a wave force ratio with $K_G = f_{Group}/f_{Single}$ where f_{Group} is the line force on a slender pile within further neighbouring piles in different arrangements and f_{Single} is line force on an isolated single pile. Among all these parameters, *KC*-number was identified as the most suitable parameter to describe the effect of wave conditions on pile group interaction (Bonakdar, 2014). Among the structure parameters, pile group arrangement and relative spacing parameter S_G/D are the most significant parameters affecting the resulting wave load on a slender pile within other neighbouring piles. This was also widely reported in literature. Overall, it can be stated that:

$$K_G = \frac{f_{Group}}{f_{Single}} = f\left\{KC, \frac{S_G}{D}, Arrangement\right\} \tag{3}$$

In the side by side arrangement, where the incident wave direction is orthogonal to the connecting line of the centres of the piles located next to each other, seven pile group configurations with relative spacing of S_G/D=0.5, 0.75, 1.0, 1.5, 2.0, 3.0 and 5.0 were tested, including a total of 146 regular non-breaking wave tests. The results illustrating the relationship between pile group effect K_G and KC number for side by side arrangement with relative spacing S_G/D=0.5 to 5 are depicted in Figure 6. The first noticeable implication to be drawn from this figure is that pile group effect K_G increases with decreasing relative spacing S_G/D as often reported in the literature (e.g. Chakrabarti, 1981; 1982; Li et al., 1993; Mindao et al., 1987; Sparboom and Oumeraci, 2006). The second important implication from Figure 6 is that for smaller KC-values (KC<30), two basically different behaviours of the relationship between K_G and KC-number are distinguished for closely-spaced piles ($S_G/D \leq 1.5$) and for largely-spaced piles (S_G/D>1.5).

For largely-spaced piles (S_G/D>1.5), K_G values are more or less the same for the whole range of KC numbers, meaning that the pile group interaction does not anymore depend on the wave conditions. This is also the case for $S_G/D \leq 1.5$ and larger KC-values (KC>30). For $S_G/D \geq 3$ data points are grouped around K_G=1 for all KC values meaning that already at this value there is no interaction between piles and each pile behaves like a single isolated pile. Mindao et al. (1987) showed that there is no significant pile group effect for the configuration with S_G/D=3. Bonakdar and Oumeraci (2012) and Sparboom et al. (2006) found no pile group interaction for S_G/D=3 for the regular non-breaking waves tested in GWK.

For closely-spaced piles ($S_G/D \leq 1.5$) where more pile group interaction is expected, the relationship between K_G and KC number is similar for all tested relative spacing S_G/D=0.5, 0.75, 1.0 and 1.5. For each of these configurations, K_G is almost constant for KC<6. This is the range below which inertia dominates and drag can be completely neglected. It can, in other words, be stated that for inertia dominant conditions (KC<6), pile group interaction is only dependent on relative spacing S_G/D and, by decreasing S_G/D, K_G increases up to 1.3 for the smallest tested spacing (S_G/D=0.5). As the pile is quite slender, KC<6 corresponds to waves with very small wave heights and periods. By increasing the KC number, pile group effect parameter K_G sharply increases and reaches its maximum for KC=13. For all closely-spaced piles ($S_G/D \leq 1.5$), the K_G values obtained for KC=10 - 20, which correspond to the range of the transition regime for drag and inertia, are indeed significantly higher than for KC<10 and KC>20 (Figure 6). The maximum K_G=2.4 is reached for the configuration with the smallest tested spacing (S_G/D=0.5). The pile group effect K_G decreases with a lower rate up to KC values of about 30~35. For KC>30~35, further increase of KC does not noticeably affect pile group effect parameter K_G and it depends only on relative spacing S_G/D. This is the case in which drag dominates and inertia is negligible.

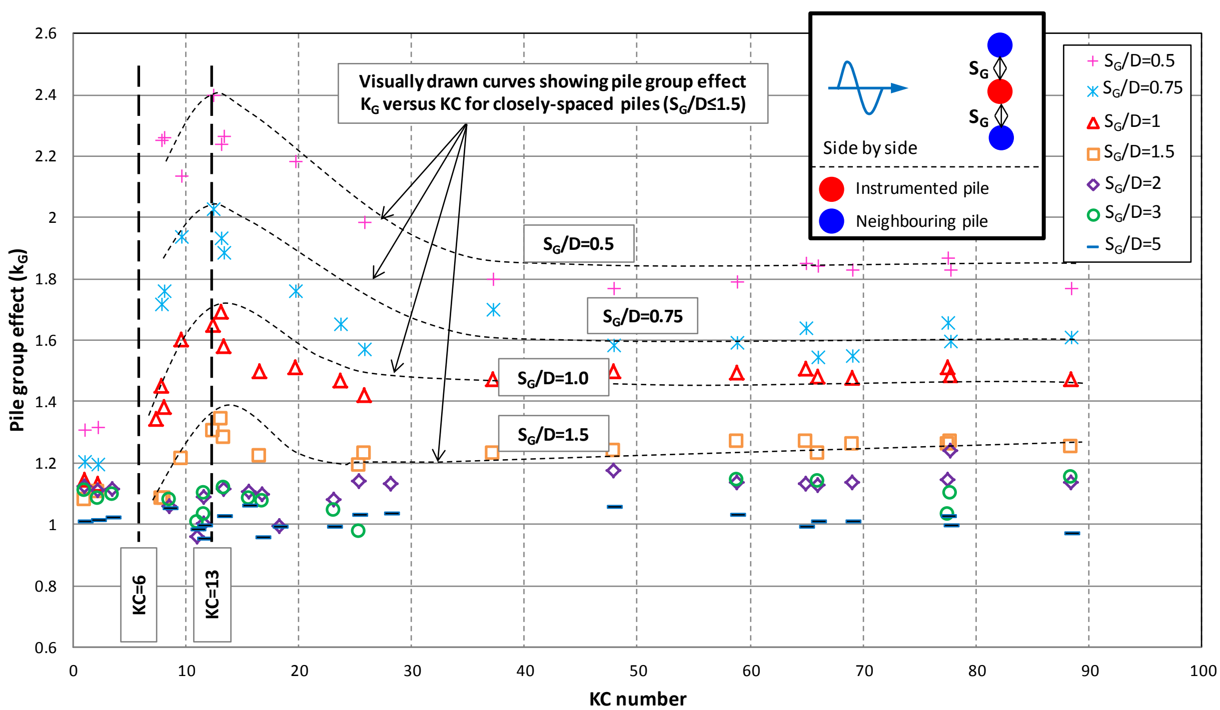


Figure 6. Relationship between pile group effect K_G and KC number for side by side arrangement exposed to regular non-breaking waves

For a better understanding of this behaviour, four curves are visually drawn to illustrate the relationship between pile group effect K_G and KC number (KC>6) for $S_G/D \leq 1.5$ named as closely-spaced piles (Figure 6). It can be concluded that the highest amplification of wave load on the middle pile in side by side arrangement occurs when KC number is about 13 where both inertia and drag are important. For the pure inertia regime (KC<6), where the water depth is relatively high and for the pure drag regime (KC>30~35), wave pile group effect K_G only depends on relative spacing S_G/D. A similar behaviour was reported by Li et al. (1993), who investigated the pile group effect of two piles in side by side arrangement subject to irregular non-breaking waves. They introduced *significant pile group effect* $K_{G1/3}$ plotted against *peak period related KC number* KC_p in Figure 7. $KC_p=u_{max}T_p/D$ was calculated based on peak wave period T_p and maximum wave-induced flow velocity u_{max} at the water surface while in the regular wave tests of this study , KC was calculated based on u_{max} measured at relative water elevation of z/h=0.78. Although a direct quantitative comparison is hardly possible between the results of Li et al. (1993) with those obtained in this study (due to differences in the wave and structure conditions as well as the different approaches used for the KC number), both results are qualitatively well-comparable.

As shown in Figure 7, significant pile group effect parameter $K_{G1/3}$ is around 1.1 for small KC number (e.g. KC_p=5) and increases with increasing KC number until it reaches its maximum around KC_p=16 for $S_C/D=(S_G/D)+1=1.5$ (S_C and S_G are the spacing between the axes of two adjacent piles and the gap between the surfaces of two neighbouring piles, respectively) which represents the smallest relative spacing tested by Li et al. (1993). By further increasing the KC number, the pile group effect decreases, which is in agreement with the result of this study (Figure 6). A further implication from Figure 7 is that by increasing S_C/D from 1.5 to 2, the location of the highest $K_{G1/3}$ slightly changes from a KC_p value of about 16 to 18. This might be due to the regression analysis applied to the data which resulted in the fitting curves drawn in Figure 7. As the data points are not shown by Li et al. (1993), it is not possible to see whether the highest $K_{G1/3}$ was obtained at different KC values for different S_C/D or not.

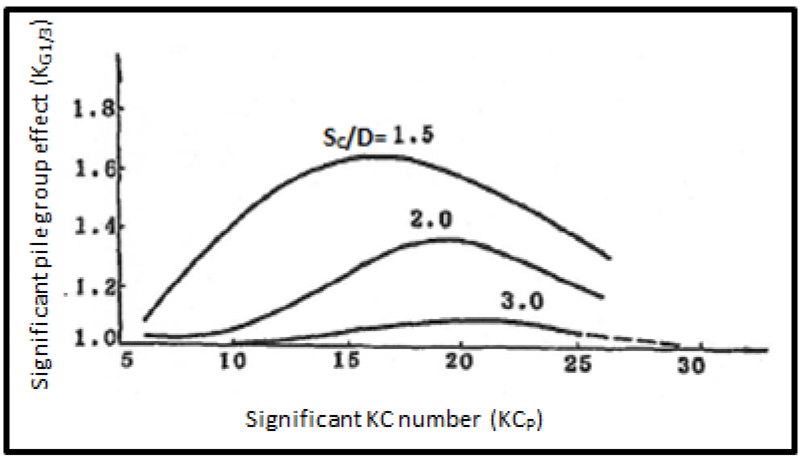


Figure 7. Relationship Pile group effect K_G for middle pile in side by side arrangement for pure-wave condition (Li et al., 1993)

5 CONCLUSIONS

Vertical array of piles exposed to regular non-breaking waves were investigated by means of laboratory tests. The type of pile group arrangement and relative spacing parameter S_G/D were found to represent the most significant structure parameters. For side by side arrangement, pile group effect K_G is a multivariate function of both hydrodynamic (KC number) and structural (S_G/D) parameters when both inertia and drag are important (6<KC<30). For this case, very high K_G values were obtained with a maximum K_G =2.4 at S_G/D=0.5. For either purely inertia (KC<6) where relative water depth is high (h/L>0.29) and purely drag (KC>30~35) wave pile group effect K_G is only a function of relative spacing S_G/D. The presented results are valid for the hydrodynamic and structure conditions tested in Phase 2 of the LWI wave flume tests as shown in Table 1 and Figure 5. The results discussed in this study is applicable for the estimation of the pile group effect through the new prediction formulae proposed and discussed in Bonakdar et al. (2015).

ACKNOWLEDGEMENT

The support of the German Research Foundation (DFG, *Deutsche Forschungsgemeinschaft*) for this study through the WaPiGS project (Ou 1/13-1 and Ou 1/13-2) is acknowledged.

REFERENCES

Bonakdar, L., 2014. Pile group effect on the wave loading of a slender pile. PhD thesis, Technische Universität Braunschweig, Germany (ISBN 978-3-86948-383-2).

Bonakdar, L., Oumeraci, H., 2012. Interaction of waves and pile group-supported offshore structures: A large scale model study. *In proceedings of 22nd International Offshore and Polar Engineering Conference (ISOPE)*, Rhodes, Greece, pp. 812 – 818.

Bonakdar, L., Oumeraci, H., 2014. Small and large scale experimental investigations of wave loads on a slender pile within closely spaced neighbouring piles. *In proceeding of 33rd International Conference on Ocean, Offshore and Arctic Engineering (OMAE)*, San Francisco, USA.

Bonakdar, L., Oumeraci, H., Etemad-Shahidi, A., 2015. Wave load formulae for prediction of wave-induced forces on a slender pile within pile groups. *Coastal Engineering*, 102, 49-68.

Chakrabarti, S. K., 1981. Hydrodynamic coefficients for a vertical tube in an array. *Applied Ocean Research*. 3, 2-12.

Chakrabarti, S. K., 1982. Inline and transverse forces on a tube array in tandem with waves. *Applied Ocean Research*. 4, 25-32.

El Safti, H., Bonakdar, L., Oumeraci, H. 2014. A Hybrid 2D-3D CFD Model System for Offshore Pile Groups Subject to Wave Loading. *33rd International Conference on Ocean, Offshore and Arctic Engineering (OMAE)*, San Francisco, USA.

Kudeih, M., Nistor, I., Cornett, A., 2010. An experimental study of wave and current-induced forces on a compact linear array of vertical cylinders in shallow water, *In proceeding of 32nd International Conference on Coastal Engineering (ICCE), ASCE*, Shanghai, China

Li, Y. Ch., Wang, F. L., Wang, H. R., 1993. Wave-current forces on vertical piles in side-by-side arrangement. *In Proceedings of 3rd International Offshore and Polar Engineering Conference (ISOPE)*, Singapore.

Mindao, G., Lihua, H., Shaoshu, S., 1987. Experimental study for the wave forces on pile groups due to regular waves. *In Proceedings of 2nd International Conference on Coastal and Port Engineering in Developing Countries (COPEDEC)*, Beijing, China, pp. 1956 – 1965.

Morison, J.R, O'Brien, M.P, Johnson, J.W, Schaaf, S. A., 1950. The force exerted by surface waves on piles. Petroleum Transactions, *AIME*, Vol. 189.

Smith, D., Haritos, N. 1997., The influence of grouping on the force characteristics of pairs of vertical surface-piercing cylinders. *In proceeding of 7th International Offshore and Polar Engineering Conference (ISOPE)*, Honolulu, USA.

Sparboom, U., Hildebrandt, A., Oumeraci, H., 2006. Group interaction effects of slender cylinders under wave attack. *In proceeding of 30th International Conference on Coastal Engineering (ICCE), ASCE*, San Diego, USA.

Sparboom, U., Oumeraci, H., 2006. Wave loads of slender marine cylinders depending on interaction effects of adjacent cylinders. *In proceedings of 25th International Conference on Offshore Mechanics and Arctic Engineering (OMAE)*, Hamburg, Germany.

Zdravkovich, M. M., 1977. Review of flow interference effects between two circular cylinders in various arrangements, *Journal of Fluids Engineering, ASME*, 99, 618-633.