De Paepe Willems Award 2017 – Third Place

WAVE FORCES ON SLENDER PILES WITHIN PILE GROUPS: LABORATORY TESTS AND PREDICTION FORMULAE FOR DESIGN PRACTICE

DR.-ING. LISHAM BONAKDAR

Leichtweiss-Institute for Hydraulic Engineering and Water Resources,
Technische Universität Braunschweig

He earned his PhD from Technische Universität Braunschweig in Coastal and Offshore Engineering. His research interest is wave-structure interaction modelling.

l.bonakdar@tu-braunschweig.de

Keywords: pile group effect, pile group arrangement, relative spacing, KC number, hybrid M5MT-GP model, wave load formulae

Mots clés : effet des groupes de piles, configuration des groupes de piles, espacement relatif, nombre KC, modèle hybride M5MT-GP, formule de charge due aux vagues

1 Introduction

Pile-supported structures commonly found in a coastal or offshore environment are generally built by means of a group of piles in different arrangements. In the offshore environment, these structures are used for offshore oil and gas platforms (Figure 1b). In the coastal environment, they are widely used in marine transportation systems, for instance for the construction of sea bridges, piers and jetties (Figure 1b).

Figure 1: Pile group-supported a) offshore platform b) coastal structure

Unlike single isolated piles, where a large number of studies are available together with the well-known Morison (1950) formula, which is still widely applied for the calculation of wave-induced force, less research studies have been made on wave-pile group interactions. In the current guidelines and standards for the design of offshore and coastal structures, no reliable wave load formula is yet available for the prediction of wave-induced forces on a slender pile within a pile group of different arrangements. To the author's knowledge, only very limited information might be found in the international standard designs of offshore structures. For instance, in DNV (2010) it is recommended that the group effect may be taken into account in the case of multiple piles without providing any further information or formula and reports that the piles in the group should be treated individually if no adequate documentation for the specific case is available. For the design of closely-spaced conductors where $S_G/D \leq 3$, API (2007) recommends applying a reduction factor named Conductor Shielding Factor to the drag and inertia coefficients for the conductor array. The recommended shieling factor is only dependent on the relative spacing (S_G/D) and influence of the wave condition is not considered. Furthermore, no recommendation is given for the cases in which the existence of neighbouring cylinders may amplify the resulting wave force. Wave loads on pile groups are not also addressed in the handbook of offshore engineering by Chakrabarti (2005). Therefore, the correct prediction of the wave loading of closely-spaced piles of these structures is vital for both safety and economical viewpoints.

The available experimental studies have contributed to enhance the knowledge about the interaction between waves and pile groups [Chakrabarti, 1979 ; Li et al., 1993 ; Mindao et al., 1987 ; Sparboom and Oumeraci, 2006 and etc.]. Nevertheless, several weaknesses still remain which should be overcome to achieve a reliable prediction of wave-induced forces on slender piles within pile groups and, consequently, a safe design of pile-supported marine structures. Therefore, the main objectives of this study 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.

This paper is outlined as follows: the laboratory data are described in Section 2. Next, the hybrid M5MT-GP model is introduced. In Section 4, the implementation of the hybrid M5MT-GP model for the analysis of the laboratory data as well as for the development of prediction formulae are provided and the obtained results are discussed. Finally, the summary of the key results and concluding remarks are drawn in Section 5.

2 Laboratory Experiments (LWI Tests)

A large number of small scale laboratory tests were carried out in the LWI wave flume, called hereafter LWI tests. The cross section of the model set-up is exemplarily drawn for the case of side by side arrangement in Figure 2. As seen, in addition to the pile group, an isolated single pile was also placed far from the pile group as a reference pile. As depicted in Figure 2, 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 were also measured by the so-called ring transducers. These three ring transducers were located at the elevations 0.14, 0.30 and 0.46 m below still water level (SWL). In other words, for each test, the local force on the small (4 cm) sections which is hereafter called line force was simultaneously measured at three different relative elevations of the water column (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 the ring transducers.

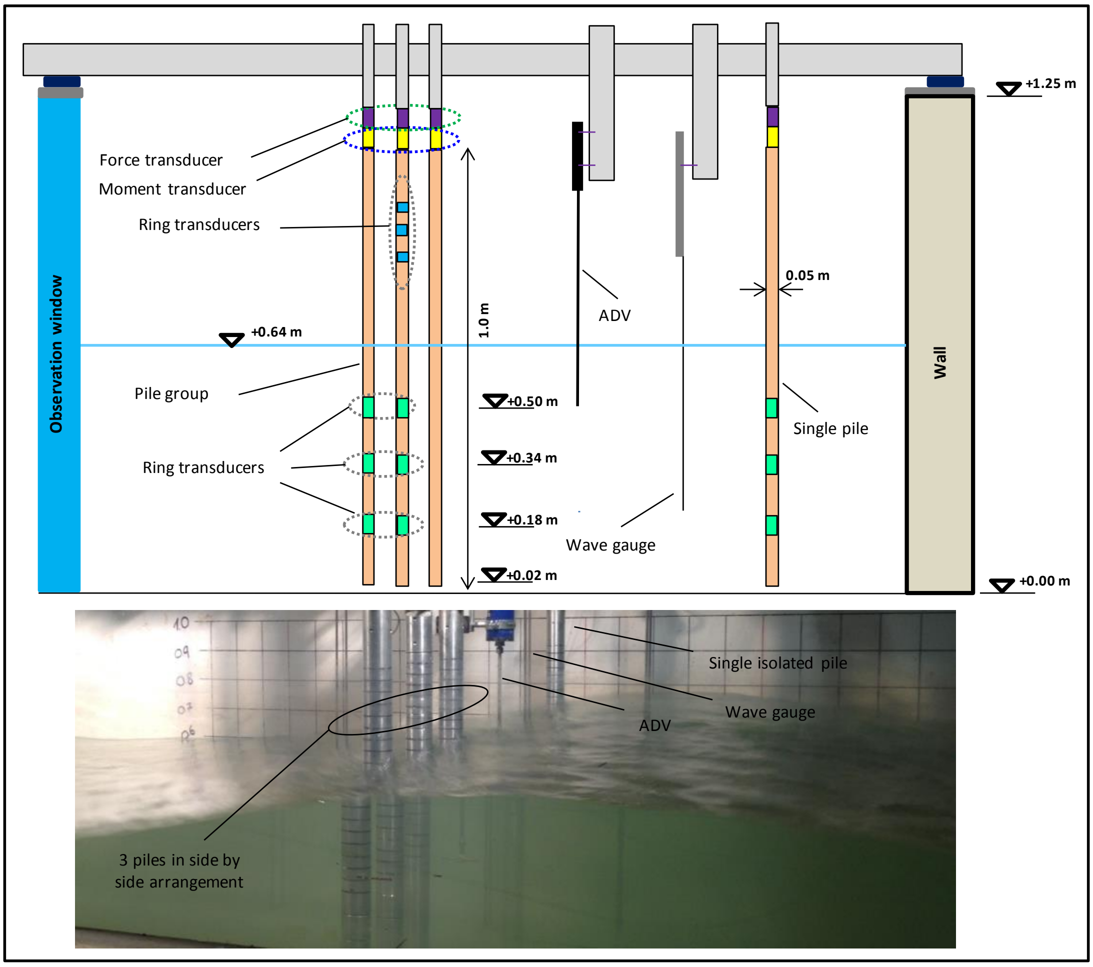


Figure 2: Model set-up of LWI tests, exemplarily for a pile group with side by side arrangement;
a) cross section;
b) snapshot: test with regular non-breaking wave

Different pile arrangements including single, side by side, tandem, 2×2 and staggered arrangements were performed and relative spacing S_G/D was varied from 0.5 to 5.0 as illustrated in Figure 3. Regular non-breaking waves with 24 different combinations of wave heights and periods were tested to cover a broad range of hydrodynamic conditions. Wave steepness varies from 0.008 to 0.073 which was the maximum possible wave steepness without having incipient breaking. Relative water depth h/L varies from 0.042 to 0.64 meaning that deep, transition and shallow water conditions were considered. The KC number changes from 1.1 where the inertia regime dominates to 88 where the drag regime dominates. Reynolds number varies from Re=0.34×10^4 to Re=3.68×10^4 indicating that the LWI model is located in the subcritical zone. The details of the model set-up, measuring technics and test programme are provided in Bonakdar (2014) and Bonakdar and Oumeraci (2015).

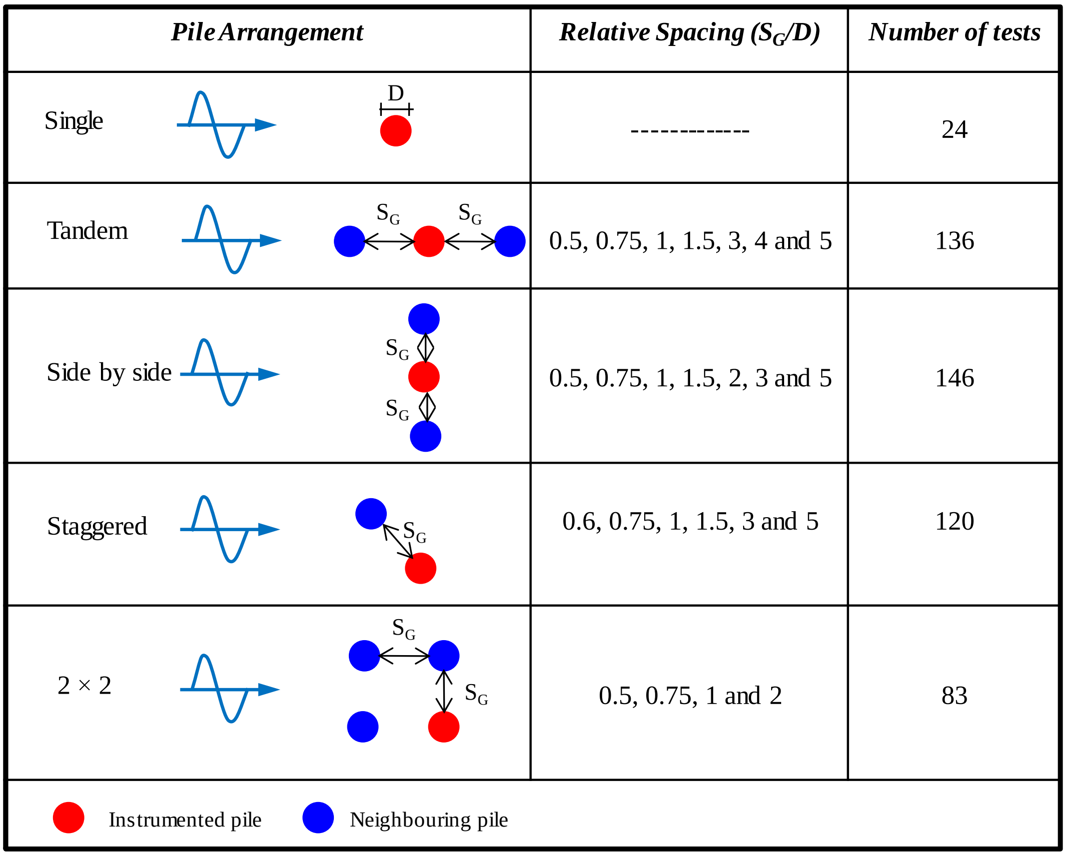


Figure 3: Pile group configurations performed in the LWI wave flume tests for non-breaking waves

3 Data Analysis Methodology

The most common method for empirical model development is the regression analysis. In the process of traditional regression analysis (e.g. simple linear, polynomial, etc.), the functional relationship between output and input parameters (variables) is pre-defined, and the goal is only to determine a set of empirical coefficients of the input parameters. For complex and unknown systems, however, a predefined functional structure may not result in an accurate model. Therefore, an artificial intelligence (AI)-based which is a combination of M5 model tree (M5MT) and genetic programming (GP) named hybrid M5MT-GP model was implemented for the analysis of the laboratory tests.

3.1 M5 Model Tree (M5MT)

The M5 model tree (M5MT) was introduced by Quinlan (1992) and represents one of the most recent computational tools for data analysis which can be applied for prediction purposes. The concept of the model tree approach is based on dividing complex problems into smaller sub-problems and solving each sub-problem. More detailed information about the M5MT is given by Wang and Witten (1997). While the traditional regression method fits a single function to the whole data set, M5 model tree splits the data points into homogeneous sub-sets (leaves) and fit a linear function for each sub-set (leaf). Sorting the whole data point into homogeneous sub-sets can result in a more accurate model which cannot be achieved by a common regression method. The major limitation of this method is that it can provide only a linear relationship between input and output parameters at each leaf, while the relationships between the output and input parameters are not necessarily linear.

3.2 Genetic Programming (GP)

Genetic Programming (GP) is an evolutionary symbolic regression method where, unlike traditional regression methods, the functional structure between output and input parameters is not pre-defined and is a result of the search process. GP was firstly introduced by Koza (1992) as a powerful tool for solving complex problem and provides a formula also called a computer programme is generated as the solution of the given problem. GP creates an initial population of functional forms from user-specified building blocks stored as *function* set, which consists of basic mathematical operators (e.g. addition, subtraction, multiplication, division, log, etc.) and constants, and the so-called *terminal* set which consists of independent variables (input parameters) and constants. These building blocks can consist of a range of operators, including addition, subtraction, multiplication, division, etc. Using a tree-based representation, the genotype is arranged such that the top and middle of the tree is created from members of the function set, and the leaves consist of members of the terminal set. Once the initial population has been created, the so-called *reproduction*, *mutation* and *crossover* are used to generate *offspring*. The best offspring (equation) resulting from this process is the solution of the problem. More detailed information about the GP might be found in Koza (1992).

3.3 Hybrid M5MT-GP Model

Considering the strengths and limitations of the M5MT and GP and making use of their respective strengths, a one-way coupling of M5MT and GP was considered for the development of wave load formulae. By this way, all data sets obtained from laboratory experiments are firstly classified in different classes based on the criteria of M5 model tree algorithm and then GP is applied to the classified data. The overview of the procedure of data analysis and the development of prediction formulae for the wave load using the hybrid M5MT-GP model is drawn in Figure 4. The details of the Hybrid M5MT-GP model are provided in Bonakdar (2014) and Bonakdar et al. (2015).

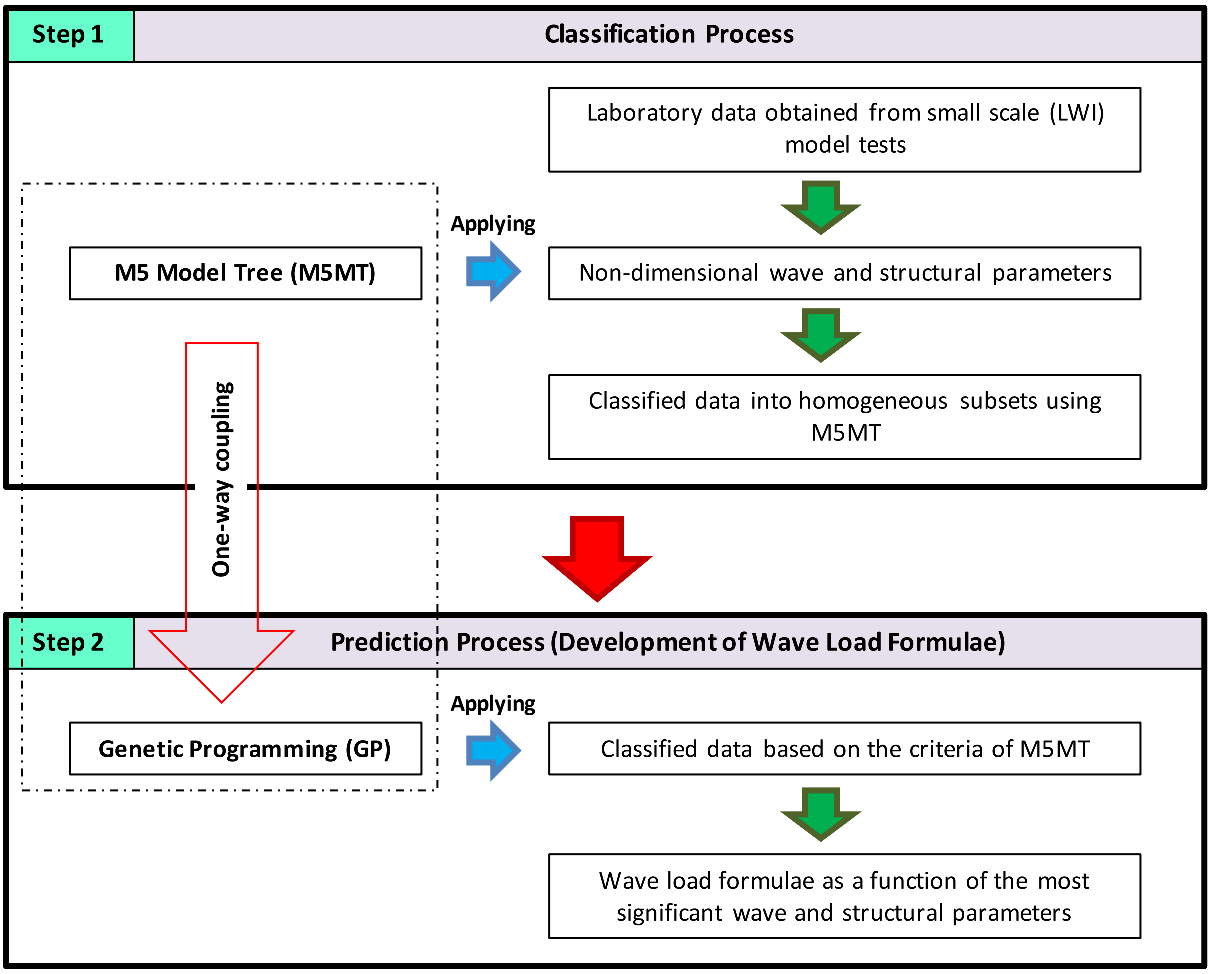


Figure 4: Overview of one-way coupled M5MT-GP modelling for data analysis and the development of new prediction wave load formulae

4 Development of Wave Load Formulae Using Hybrid M5MT-GP Model

4.1 Data Classification Using M5MT

Before classifying the data using M5MT, a comprehensive analysis on the effect of non-dimensional wave parameters including *KC* number, Reynolds number *Re*, relative water depth *h/L* and wave steepness *H/L* on pile group effect K_G was made by Bonakdar 2014. The latter represents the relative wave force ratio ($K_G=f_{Group}/f_{Single}$) where f_{Group} is the maximum line force on a slender pile within a pile group in different arrangements and f_{Single} is the maximum 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. It was stated that pile group effect K_G related to *KC* number is more appropriate than that related to other non-dimensional wave parameters. In addition, *KC* number is a function of both wave period and flow velocity which make it an appropriate parameter for describing wave-induced flow conditions. Therefore, *KC* number was favoured as a parameter describing the flow regime for the development of wave load formulae. From the structural point of view, 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. Overall, it can be stated that:

$$K_G = \frac{f_{Group}}{f_{Single}} = f\left\{KC, \frac{S_G}{D}, Pile\ group\ arrangement\right\} \tag{1}$$

Different pile group arrangements including side by side, tandem, staggered and 2×2 were individually analysed by M5MT. Pile group effect K_G was set as the output while *KC* number and relative spacing S_G/D were set as the inputs of the model representing the most relevant influencing hydrodynamic and structural parameter, respectively.

4.1.1 Side By Side Arrangement

Figure 5 illustrates the relationship between pile group effect K_G and *KC* number for side by side arrangement as well as the developed tree showing splitting parameters and the corresponding splitting values at nodes and leaves (sub-sets), where data points are finally classified. The classified sub-sets are also demonstrated by manually drawn dash lines. As seen, M5MT classified all data into 5 different sub-sets based on different combinations of *KC* number and relative spacing S_G/D. The first splitting parameter located at the root of the inverse tree is relative spacing S_G/D and its splitting value is 1.5. As discussed by Bhattacharya et al. (2007), the splitting value does not necessarily have any physical interpretation and is obtained by minimizing the prediction error. However, this value distinguishes the so-called 'closely-spaced piles' ($S_G/D\leq1.5$) where a greater pile group interaction is expected from 'largely-spaced piles' ($S_G/D>1.5$) where less interaction of piles occurs due to larger gaps between piles.

For the configurations with $S_G/D\leq1.5$, where the piles are closely spaced next to each other in an array, *KC* number becomes important. As seen on the left-hand side of the tree shown in Figure 5, data points with $S_G/D\leq1.5$ were grouped by *KC* number with the splitting value of 13. As shown by the dash-line, this is almost the value at which maximum amplification of wave load on the closely-spaced piles in side by side arrangement occurs. Data with $S_G/D\leq1.5$ and $KC>13$ was classified only in one group (sub-set 3 in Figure 5). For data with $S_G/D\leq1.5$ and $KC<13$, another categorization is made by *KC* number as shown on the down-left hand side of the tree. The values that came down from the root through the branch to this node, were classified into two other group at $KC=6$. Pile group effect K_G is almost constant when *KC* is smaller than 6 (inertia dominated regime, sub-set 1) and shows different behaviour for the cases with $KC>6$ (sub-set 2 in Figure 5).

For the configurations with $S_G/D>1.5$, data points were sorted into two groups according to relative spacing parameter S_G/D with a splitting value of 2. As seen in Figure 5, K_G values are more or less the same for the whole range of *KC* values, meaning that pile group interaction is not dependent on the hydrodynamic conditions for $S_G/D>1.5$. The data associated with each leaf will be considered for the development of prediction formulae using GP as M5MT can only generate a linear relationship between output and input parameters.

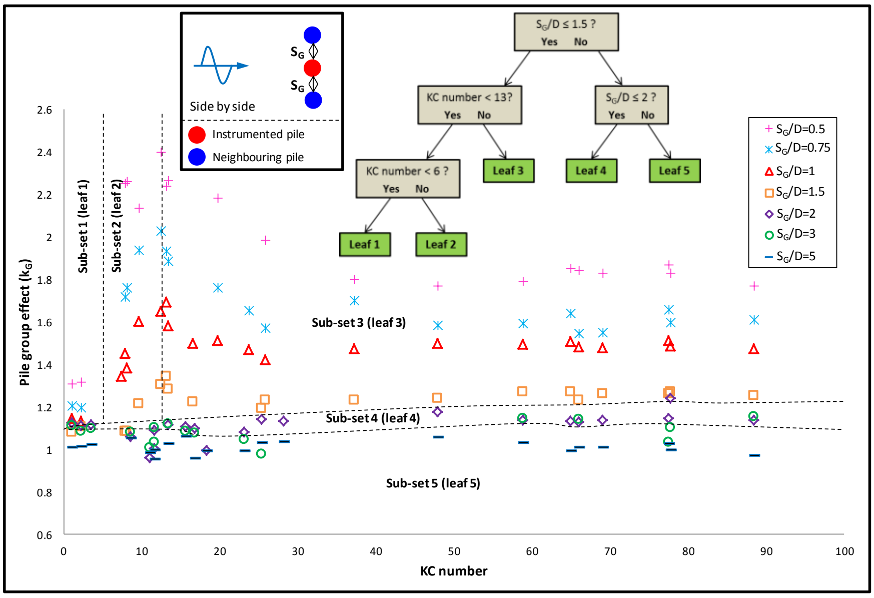


Figure 5: Developed M5MT model for side by side arrangement and relationship between pile group effect K_G and KC number for different S_G/D

4.1.2 Tandem Arrangement

In total, 136 data were classified by M5MT for this arrangement. As seen in Figure 6, the developed tree is very simple and has only one root (node) and two leaves. All 136 data points were sorted into two groups based on S_G/D with a splitting value of 3. This is also demonstrated by the manually drawn dash-line splitting data with $S_G/D \le 3$ from the rest of the data. It is apparent from the developed tree that the data points were not categorised by *KC* number which was one of the inputs of the model meaning that M5MT discovered a similar relationship between K_G and *KC* number for different pile configurations with $S_G/D \le 3$ (sub-set 1 in Figure 6). For the configurations with $S_G/D > 3$, where piles are fairly far from each other, data points were sorted into another group (sub-set 2 in Figure 11). In this case K_G values are grouped around $K_G=1$ for all *KC* values indicating that there is no interaction between piles and each pile behaves like a single isolated pile (Figure 6).

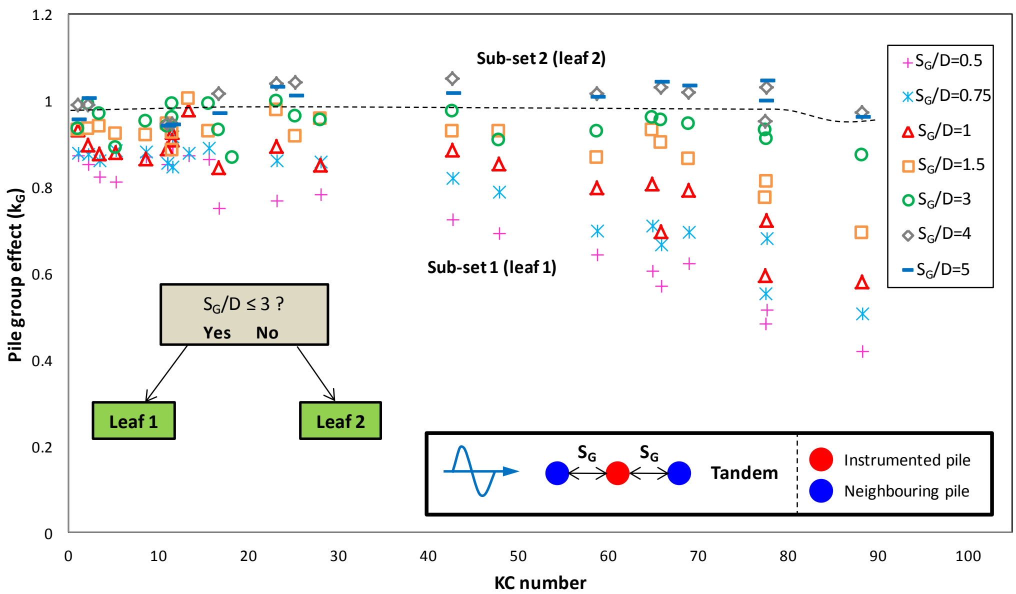


Figure 6: Developed M5MT model for tandem arrangement and relationship between pile group effect K_G and KC number for different S_G/D

4.1.3 2×2 Arrangement

The relationship between pile group effect K_G and KC number for the 2×2 arrangement is shown in Figure 7. The most interesting indication from Figure 7 is that the pile group interaction of 2×2 arrangement is clearly a combination of both pile group interactions observed in side by side and tandem arrangement. This means that both wave load amplification seen in side by side (Figure 5) and sheltering effect observed in tandem arrangement (Figure 6) can be seen in the so called 2×2 arrangement.

The first splitting parameter shown at the root of the inverse tree is relative spacing S_G/D and its splitting value is 1.5. Next, for cases with S_G/D>1.5 and S_G/D≤1.5, KC number appears as the splitting parameter. In both nodes, the corresponding splitting value is 6. This means that in both closely-spaced piles (S_G/D≤1.5) and S_G/D>1.5 M5MT model found different physical behaviours in the data for KC<6 (sub-sets 1 and 3 in Figure 7) where the resulting wave load on the pile is primarily dominated by inertia and KC>6 (sub-sets 2 and 4 in Figure 7) where both inertia and drag forces are important.

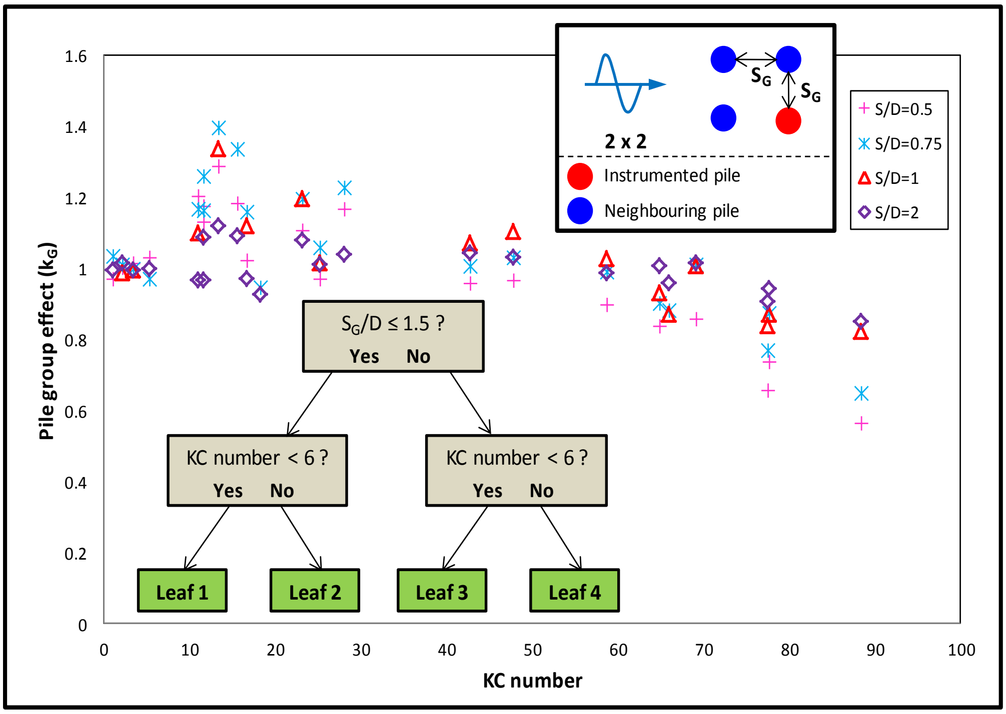


Figure 7: Developed M5MT model for 2×2 arrangement and relationship between pile group effect K_G and KC number for different S_G/D

4.1.4 Staggered Arrangement

Six different pile group configurations with relative spacing of S_G/D=0.6, 0.75, 1.0, 1.5, 3.0 and 5.0 were used for staggered arrangement where the angle between incident waves and the axis of pile groups is 45°. Fig. 8 demonstrates the relationship between pile group effect K_G and KC number for staggered arrangement with different S_G/D. As seen, no specific relationship can be seen between pile group effect K_G and KC number for the tested pile configurations with different S_G/D values and almost all of the data points for different wave and structural conditions vary between 0.9 and 1.1. Applied M5MT model did not classify data points into different sub-sets and only represented a model with only one leaf. In fact, K_G=1 was found as the best fitting line to data points for the downstream pile in staggered arrangement. This result is not, however, unexpected as the K_G values obtained for staggered arrangement (45°) are between those gained for side by side (90°) and tandem (0°) arrangements.

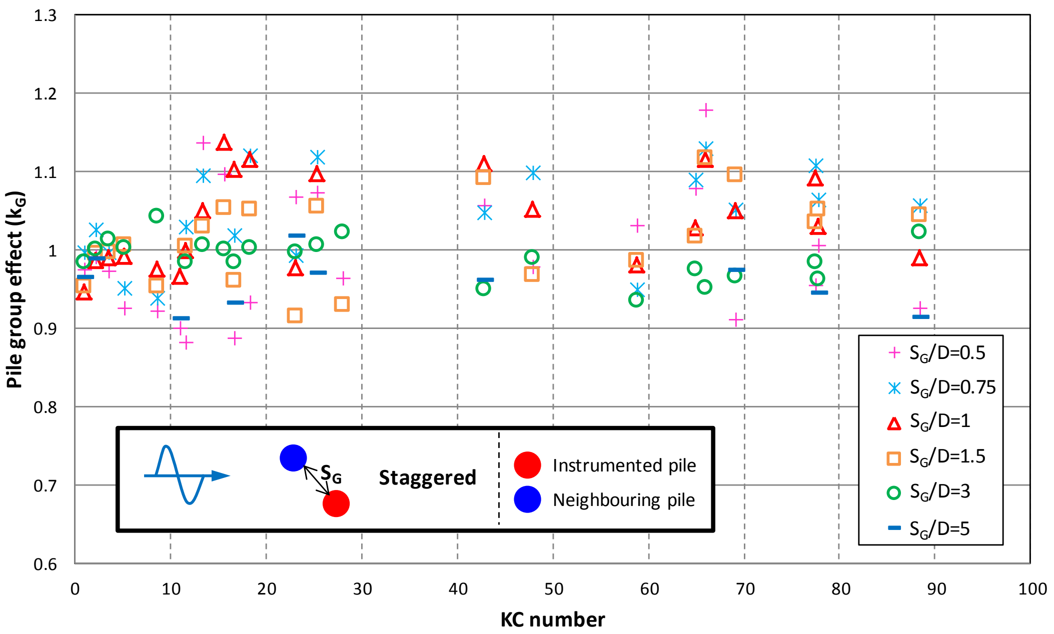


Figure 8: Relationship between pile group effect K_G and KC number for staggered arrangement

4.1.5 Overall M5MT Model

An overall model can be proposed including all generated models as constituents (Figure 9). As seen, the complete model, which consists of all models individually developed for each pile group arrangements, has 12 sub-sets (leaves) named from A to L. The first splitting parameter located at the root of the inverse tree is relative spacing S_G/D and the splitting value is 1.5. The pile group configurations with $S_G/D \leq 1.5$ were named 'closely-spaced piles' where a greater pile group interaction is expected. The second splitting criterion of M5MT model is the pile group arrangement at the second node of the inverse tree based on which an appropriate arrangement is chosen among the four tested arrangements including side by side, tandem, 2×2 and staggered arrangements. From this node, depending on the type of pile group arrangement, further splitting parameters including *KC* number and relative spacing S_G/D might become important and play a role in sorting data. By this way, further categorisations of a test might be made depending on its specific wave and structural conditions and it reaches the final node called leaf through the branches.

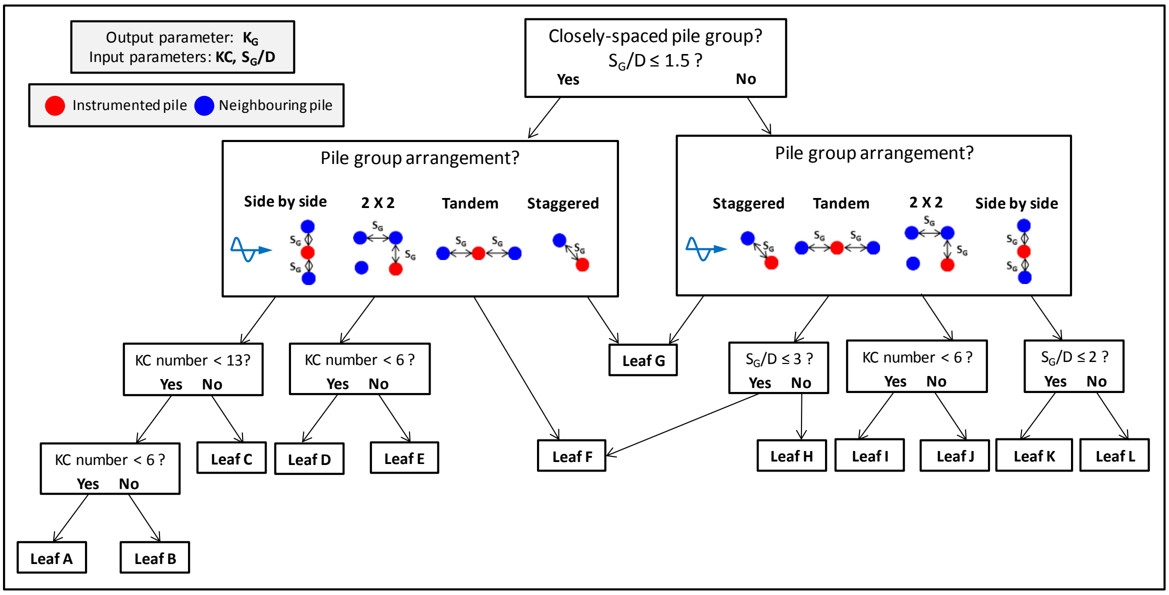
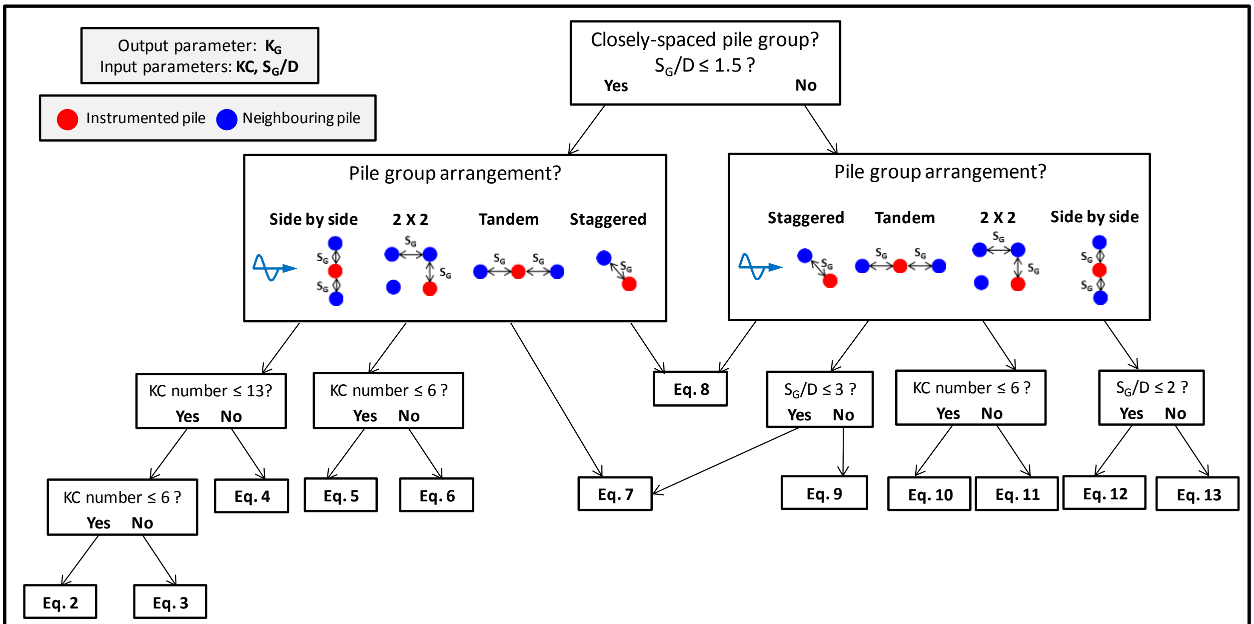


Figure 9: Overall M5MT model for different pile group arrangements exposed to non-breaking waves

4.2 Development of Wave Load Formulae Using GP

After the classification of data into sub-sets performed by means of the M5MT model, the prediction was made by applying the GP model to the data associated with each leaf. For each pile group arrangement, like for M5MT, *KC* number and relative spacing S_G/D were used as the inputs of GP models while pile group effect K_G was considered as the output parameter. These parameters were, indeed, the *terminal set* of the GP model. For the *function set*, however, different mathematical operators were tested in order to optimise the GP model and, consequently, to obtain the best solution (formula). Two main criteria were considered for selecting the best solution (formula) among a large number of possible solutions that can be developed by GP. These two main criteria were accuracy and simplicity of the possible solution. The individual GP models developed and optimised for each type of the pile group arrangements were brought together to build the overall M5MT-GP model and developed formulae shown in Figure 10.



Eq. 2:	$K_G = \frac{f_{Group}}{f_{Single}} = 1.14\left(\frac{S_G}{D}\right)^{-0.19}$	*for side by side, $S_G/D \le 1.5$ & $KC \le 6$*
Eq. 3:	$K_G = \frac{f_{Group}}{f_{Single}} = 0.87\left(\frac{S_G}{D}\right)^{-0.51}(KC)^{0.26}$	*for side by side, $S_G/D \le 1.5$ & $6 < KC \le 13$*
Eq. 4:	$K_G = \frac{f_{Group}}{f_{Single}} = 1.4\left(\frac{S_G}{D}\right)^{-0.46}\exp\left(52.7(KC)^{-2.22}\right)$	*for side by side, $S_G/D \le 1.5$ & $KC > 13$*
Eq. 5:	$K_G = \frac{f_{Group}}{f_{Single}} = 1$	*for 2x2 arrangement, $S_G/D \le 1.5$ & $KC \le 6$*
Eq. 6:	$K_G = \frac{f_{Group}}{f_{Single}} = 1.4 - 0.136\left(\frac{S_G}{D}\right)^{-0.32}\exp\left(\frac{KC}{56}\right)$	*for 2x2 arrangement, $S_G/D \le 1.5$ & $KC > 6$*
Eq. 7:	$K_G = \frac{f_{Group}}{f_{Single}} = 1 - 0.074\left(\frac{S_G}{D}\right)^{-0.8}\exp\left(\frac{KC}{56}\right)$	*for tandem, $S_G/D \le 3$*
Eq. 8:	$K_G = \frac{f_{Group}}{f_{Single}} = 1$	*for staggered*
Eq. 9:	$K_G = \frac{f_{Group}}{f_{Single}} = 1$	*for tandem, $S_G/D > 3$*
Eq. 10:	$K_G = \frac{f_{Group}}{f_{Single}} = 1$	*for 2x2 arrangement, $S_G/D > 1.5$ & $KC \le 6$*
Eq. 11:	$K_G = \frac{f_{Group}}{f_{Single}} = 1.1 - 0.013\exp\left(\frac{KC}{30}\right)$	*for 2x2 arrangement, $S_G/D > 1.5$ & $KC > 6$*
Eq. 12:	$K_G = \frac{f_{Group}}{f_{Single}} = 1.1$	*for side by side & $1.5 < S_G/D \le 2$*
Eq. 13:	$K_G = \frac{f_{Group}}{f_{Single}} = 1$	*for side by side & $S_G/D > 2$*

Figure 10: Overall M5MT-GP model and developed formulae for different pile group arrangements

This overall model includes (i) M5MT model classifying the entire data sets and (ii) GP-based formulae developed for the classified data (Eqs. 2-13).

$$K_G = \frac{f_{Group}}{f_{Single}} = 1.14\left(\frac{S_G}{D}\right)^{-0.19} \qquad \textit{for side by side, } S_G/D \le 1.5 \ \& \ KC \le 6 \qquad (2)$$

$$K_G = \frac{f_{Group}}{f_{Single}} = 0.87\left(\frac{S_G}{D}\right)^{-0.51}\left(KC\right)^{0.26} \qquad \textit{for side by side, } S_G/D \leq 1.5 \ \& \ 6 < KC \leq 13 \tag{3}$$

$$K_G = \frac{f_{Group}}{f_{Single}} = 1.4\left(\frac{S_G}{D}\right)^{-0.46}\exp\left(52.7\left(KC\right)^{-2.22}\right) \qquad \textit{for side by side, } S_G/D \leq 1.5 \ \& \ KC > 13 \tag{4}$$

$$K_G = \frac{f_{Group}}{f_{Single}} = 1 \qquad \textit{for } 2\times2 \textit{ arrangement, } S_G/D \leq 1.5 \ \& \ KC \leq 6 \tag{5}$$

$$K_G = \frac{f_{Group}}{f_{Single}} = 1.4 - 0.136\left(\frac{S_G}{D}\right)^{-0.32}\exp\left(\frac{KC}{56}\right) \qquad \textit{for } 2\times2 \textit{ arrangement, } S_G/D \leq 1.5 \ \& \ KC > 6 \tag{6}$$

$$K_G = \frac{f_{Group}}{f_{Single}} = 1 - 0.074\left(\frac{S_G}{D}\right)^{-0.8}\exp\left(\frac{KC}{56}\right) \qquad \textit{for tandem arrangement } \& \ S_G/D \leq 3 \tag{7}$$

$$K_G = \frac{f_{Group}}{f_{Single}} = 1 \qquad \textit{for staggered arrangement} \tag{8}$$

$$K_G = \frac{f_{Group}}{f_{Single}} = 1 \qquad \textit{for tandem arrangement } \& \ S_G/D > 3 \tag{9}$$

$$K_G = \frac{f_{Group}}{f_{Single}} = 1 \qquad \textit{for } 2\times2 \textit{ arrangement, } S_G/D > 1.5 \ \& \ KC \leq 6 \tag{10}$$

$$K_G = \frac{f_{Group}}{f_{Single}} = 1.1 - 0.013\exp\left(\frac{KC}{30}\right) \qquad \textit{for } 2\times2 \textit{ arrangement, } S_G/D > 1.5 \ \& \ KC > 6 \tag{11}$$

$$K_G = \frac{f_{Group}}{f_{Single}} = 1.1 \qquad \textit{for side by side arrangement } \& \ 1.5 < S_G/D \leq 2 \tag{12}$$

$$K_G = \frac{f_{Group}}{f_{Single}} = 1 \qquad \textit{for side by side arrangement } \& \ S_G/D > 2 \tag{13}$$

The proposed M5MT-GP model is quite simple, compact and easy to use. For the purpose of this study, the first question to be answered is about the value of relative spacing S_G/D between the piles, as shown at the root of the inverse tree. The case will be identified either as 'closely-spaced pile group' for $S_G/D \leq 1.5$ and 'largely spaced pile group' for $S_G/D > 1.5$. Next, the pile group arrangement should be determined, including, side by side, 2×2, tandem and staggered arrangements as drawn at the second node of the inverse tree. From this stage on and depending on the type of pile group arrangement, KC number, relative spacing S_G/D or both might need to be considered for further classifications. Finally, M5MT leads to the appropriate leaf (class) based on the related hydrodynamic and structural conditions. At this step, equation number at the leaf determines which GP-based formula to be applied for the calculation of pile group effect K_G of the instrumented pile within a pile group for the specific case considered.

The performance of the developed M5MT-GP-based formulae was quantitatively evaluated using statistical indicators such as agreement index I_a, correlation coefficient CC, scatter index SI, and $Bias$ defined as follow:

$$I_a = 1 - \frac{\sum_{i=1}^{n}(x_i - y_i)^2}{\sum(|x_i - \overline{x}| + |y_i - \overline{y}|)^2} \tag{14}$$

$$CC = \frac{(1/n)[(x_i - \overline{x})^T (y_i - \overline{y})]}{\sqrt{(1/n)(x_i - \overline{x})^2}\sqrt{(1/n)(y_i - \overline{y})^2}} \tag{15}$$

$$SI = \frac{\sqrt{1/n\sum(y_i - x_i)^2}}{\overline{x}} \tag{16}$$

$$Bias = \overline{y} - \overline{x} \tag{17}$$

where x_i and y_i denote the predicted and the measured values, respectively and n is the number of measurements (data). $\overline{x}$ and $\overline{y}$ are the corresponding mean values of the predicted and measured parameters. The scatter diagram of the measured and predicted K_G values is drawn in Figure 11 for all 485 data points used for the development of the M5MT-GP model. As seen, the predicted and measured K_G values are in a very good agreement and the scatter between them is very small as the data points are concentrated around the optimal line. Though only K_G=1 was obtained for the staggered arrangement with different wave and structural conditions, values of the statistical parameters indicate that the developed M5MT-GP model can precisely reproduce the experimental results for non-breaking wave loads on a slender pile in a group of piles. As shown in Figure 11, the agreement index (I_a) and scatter index (SI) of the model for 485 tests are, 0.987 and 5.8 %, respectively.

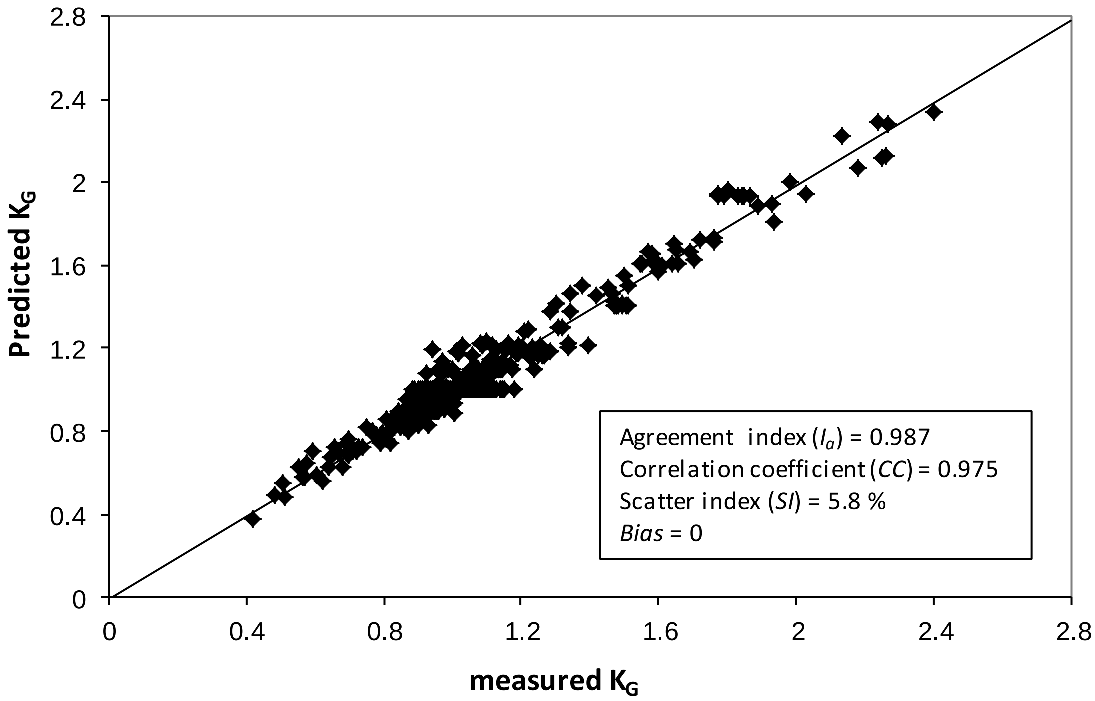


Figure 11: Comparison of predicted and measured K_G for 485 data used for the development of M5MT-GP model

5 Summary and Concluding Remarks

Small-scale laboratory tests were performed in the LWI wave flume to investigate non-breaking wave load on a slender pile within a group of piles in different arrangements. For this aim, a test programme was considered covering a broad range of wave conditions (deep to shallow water) and pile group configurations. The obtained key results may be summarised as follows:

(i) Pile group arrangement, relative spacing S_G/D and KC number were found as the most significant parameters affecting wave-induced loads on a slender pile within a pile group.

(ii) For side by side arrangement, when KC is between 6 and ~35, for which both inertia and drag are important, pile group effect K_G is a multivariate function of both hydrodynamic (KC) and structural (S_G/D) parameters. In this case, very high K_G values (up to 2.4 at S_G/D=0.5) are obtained. For the pure inertia regime (KC<6) where the water depth (h/L=0.29 – 0.64) is relatively large and for the pure drag regime (KC>30~35) wave pile group effect K_G is independent of KC and only a function of relative spacing S_G/D.

(iii) For tandem arrangement, the highest sheltering effect is obtained for very large KC number (KC=88), where the wave load is primarily dominated by drag. Sheltering effect disappears for S_G/D>3 and K_G values are more or less equal to 1 for the whole tested range of KC number.

(iv) For the 2×2 arrangement, the downstream piles behave like in both side by side and tandem arrangement.

(v) For staggered arrangement, no specific relationship could be found between pile group effect K_G and KC number. In fact, K_G varies from 0.9 to 1.1 for almost all performed tests. Therefore, the influence of wave direction on the resulting wave load on a pile in a pile group needs further investigations by testing pile group arrangements with different angles (0°-90°) of the centre connection line of the cylinders relative to the wave direction.

For the analysis of the laboratory data and development of the wave load formulae, an artificial intelligence (AI), named ‘hybrid M5MT-GP model’, was implemented. The developed M5MT-GP model and formulae are summarized in Figure 10. The developed model and formulae are simple, compact, transparent and physically-based and allow us to systematically assess pile group effect K_G depending on the flow regime (KC) and the structural conditions (pile group arrangement, S_G/D). The proposed wave load formulae are expected to fill up the current gap in the design guidelines and standards related to pile-group supported structures in offshore, coastal and harbour engineering. In addition to the proposed wave load formulae and as a result of the analysis of the described laboratory tests, new wave run-up formulae for design practice are also proposed for the prediction of wave run-up on vertical piles due to regular waves, which are recently addressed by Bonakdar et al. (2016).

6 Acknowledgments

The laboratory tests were performed within the framework of WaPiGS project (Ou 1/13-1 and 2) funded by the German Research Foundation (DFG). The presented study was conducted within the author's doctoral studies at the Leichtweiss-Institute, Technische Universität Braunschweig. Financial support of the German Academic Exchange Service (DAAD) for the author's doctoral studies is gratefully acknowledged. The author would like to express his greatest gratitude to his doctoral supervisor, Prof. Hocine Oumeraci, for the constant guidance and support.

7 References

API RP 2A (WSD) (2007): “Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms – Working Stress Design”, 21st ed, American Petroleum Institute.

Bhattacharya, B., Price, R. K. and Solomatine, D. P. (2007): “Machine Learning Approach to Modeling Sediment Transport”, J. of Hydr. Eng. 133(4), p. 440-450.

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. and Oumeraci, H. (2015): “Pile group effect on the wave loading of a slender pile: a small-scale model study”, Ocean Engineering, 108, p. 449-461.

Bonakdar, L., Oumeraci, H. and Etemad-Shahidi, A. (2015): “Wave load formulae for prediction of wave-induced forces on a slender pile within pile groups”, Coastal Engineering, 102, p. 49-68.

Bonakdar, L., Oumeraci, H. and Etemad-Shahidi, A. (2016): “Run-up on vertical piles due to regular waves: Small-scale model tests and prediction formulae”, Coastal Engineering, 118, p. 1-11.

Chakrabarti, S. K. (1979): “Wave forces on vertical array of tubes”, In proceeding of Civil Engineering in the Oceans, ASCE, San Francisco, USA, p. 241-259

Chakrabarti, S. K. (2005): “Handbook of Offshore Engineering”, Elsevier.

DNV (2010): “DNV recommended practice DNV-RP-C205. In: Environmental conditions and environmental loads”, Norway: Det Norske Veritas.

Koza, J. R. (1992): “Genetic programming: on the programming of computers by means of natural selection”, MIT Press, Cambridge, MA.

Li, Y. Ch., Wang, F. L. and 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. and 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), China Ocean Press, Beijing, p. 1956 – 1965.

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

Quinlan, J. R. (1992): “Learning with continuous classes”, In Proceedings of AI'92 (Adams and Sterling Eds), World Scientific, p. 343-348.

Sparboom, U. and 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.

Wang, Y. and Witten, I.H. (1997): “Induction of model trees for predicting continuous lasses”, In Proceedings of the Poster Papers of the European Conference on Machine Learning, University of Economics, Faculty of Informatics and Statistics, Prague.

ABSTRACT

Wave-induced loading of slender piles is among the most uncertain issues in the design of pile group-supported marine structures. Though the correct estimation of the wave loading of a pile within a pile-group in different arrangements is crucial for both safety and costs, no reliable wave load formula is available in the current guidelines and standards for the design of offshore structures. Therefore, new wave load formulae are proposed in this paper which are derived from systematic laboratory tests on the pile group effect on the wave loading of a slender pile within the author's PhD research at Leichtweiss-Institute (LWI), Technische Universität Braunschweig, in Germany. The experiments, with a focus on regular non-breaking waves, include different pile arrangements (single, side by side, tandem, 2×2 and staggered with relative spacing of S_G/D=0.5 – 5) and cover a wide range of KC-numbers (KC=1-88) and relative water depths (h/L= 0.042 - 0.64). The new wave load formulae, developed using a so-called Hybrid M5MT-GP model, allow us to systematically account for the pile group effect (K_G) as a function of the flow regime (KC number) and the relative spacing (S_G/D) for each tested pile group arrangement. The results show that the pile group effect needs to be considered in calculating wave loads on the slender piles in pile groups, unless K_G=1, meaning that there is no interference effect between neighbouring piles and that each pile in the group can be treated as a single isolated pile.

RESUME

Les charges dues aux vagues sur les piles minces sont un des problèmes les plus incertains dans la conception des structures maritimes supportées par des groupes de piles. Bien que l'estimation correcte des charges dues aux vagues sur une pile intégrée dans un groupe de piles en différentes configurations soit cruciale à la fois pour la sécurité et les coûts, aucune formule fiable n'existe dans les recommandations courantes et les standards de conception des structures offshore. Par conséquent, de nouvelles formules sont proposées dans cet article. Elles dérivent d'essais de laboratoires systématiques sur l'effet des groupes de piles sur les charges dues aux vagues d'une pile mince, dans le cadre de la thèse de l'auteur à l'institut Leichtweiss (LWI) de l'université technique de Braunschweig en Allemagne. Les expérimentations, avec un focus sur les vagues régulières non déferlantes, incluent différentes configurations de piles (isolées, côte à côte, en tandem, 2 par 2 et espacées avec un espace régulier de SG/D=0.5 – 5) et couvrent une large gamme de valeurs de KC (1 à 88) et de profondeurs relatives (h/L= 0.042 à 0.64). La nouvelle formule de charge due aux vagues, développée en utilisant un modèle dit hybride M5MT-GP, permet de tenir compte de l'effet de groupe (KG) comme fonction du régime hydraulique (nombre KC) et de l'espacement relatif (SG/D) pour chaque configuration testée. Les résultats montrent que l'effet des groupes de piles doit être considéré lors du calcul des charges dues aux vagues sur les piles minces dans des groupes de piles, à moins que KG=1 ce qui signifie qu'il n'y pas d'interférence entre piles voisines et chacune peut être traitée de manière isolée.

ZUSAMMENFASSUNG

Wellenbedingte Belastung von schlanken Pfählen ist einer der unsichersten Faktoren bei der Gestaltung von Pfahlgruppen, die marine Anlagen stützen. Obwohl die richtige Einschätzung der Wellenbelastung eines Pfahls innerhalb einer Pfahlgruppe in unterschiedlichen Anordnungen sowohl für die Sicherheit als auch für die Kosten wesentlich ist, gibt es in den aktuellen Richtlinien und Normen für die Auslegung von Offshore-Anlagen keine verlässlichen Wellenlastformeln. Daher werden in diesem Artikel neue Wellenlastformeln vorgeschlagen, die aus systematischen Labortests zum Pfahlgruppeneffekt auf die Wellenbelastung eines schlanken Pfahls abgeleitet werden, welche im Rahmen der Dissertation des Autors am Leichtweiß-Institut (LWI), Technische Universität Braunschweig, Deutschland, durchgeführt wurden. Die Experimente, die sich auf regelmäßige, nicht brechende Wellen konzentrieren, umfassen verschiedene Pfahlanordnungen (einzeln, nebeneinander, Tandem, 2 x 2 und versetzt mit einem relativen Abstand von SG/D = 0.5 – 5) und decken einen großen Bereich von KC-Zahlen (KC = 1 - 88) und relativen Wassertiefen (h/L = 0.042 - 0.64) ab. Die neue Wellenlastformel, die mit Hilfe eines

sogenannten Hybrid M5MT-GP Modells entwickelt wurde, erlaubt eine systematische Berechnung des Pfahlgruppeneffekts (*KG*) für jede getestete Pfahlgruppenanordnung als Funktion des Abflussregimes (*KC*-Zahl) und des relativen Abstands (*SG/D*). Die Ergebnisse zeigen, dass der Pfahlgruppeneffekt bei der Berechnung von Wellenbelastungen auf schlanke Pfähle innerhalb von Pfahlgruppen berücksichtigt werden muss, es sei denn, *KG* = 1, was bedeutet, dass es keinen Störeffekt zwischen benachbarten Pfählen gibt und dass jeder Pfahl in der Gruppe als einzelner, isolierter Pfahl behandelt werden kann.

RESUMEN

Las cargas derivadas de la acción del oleaje sobre pilotes esbeltos es una las las cuestiones más inciertas en el diseño de estructuras marítimas sustentadas por grupos de pilotes. Una correcta estimación de los esfuerzos en estos casos resulta un elemento crucial, tanto para asegurar las condiciones de seguridad, como un adecuado coste de la estructura, sin que en la literatura y normativa técnica disponible se puedan encontrar formulaciones de suficiente confianza para su aplicación en estructuras exteriores expuestas. En estas condiciones, en el presente trabajo se propone una nueva fórmula derivada de los resultados obtenidos en ensayos de laboratorio llevados a cabo sobre estructuras conformadas por grupos de pilotes esbeltos, en el marco de la obtención del título de Doctor por parte del autor en Instituto Técnico Leichtweiss de la Universidad Braunschweig, en Alemania. Los experimentos, basados en oleaje regular no rompiente, incluyen diversas configuraciones de pilotes (aislados, contiguos, en tandem, 2x2, y colocados con una separación relativa a su diámetro en ratios de entre 0,5 y 5), cubriendo una amplia gama del parámetro KC (entre 1 y 88) y con profundidades relativas (*h/L*) en el entorno de 0.042 a 0.64. La nueva fórmula de cálculo de cargas, desarrollada utilizando el denominado modelo híbrido M5MT-GP, permite tener en cuenta el efecto grupo en los pilotes (KG) en función del régimen con que se comporta el flujo de agua (parámetro KC) y la distancia relativa (SG/D) para cada disposición de grupos de pilotes. Los resultados muestran que el efecto grupo debe tenerse en consideración a la hora de calcular las fuerzas del oleaje en una estructura, a menos que KG sea igual a 1, en cuyo caso no existirá interferencia entre elementos, de tal manera que cada pilote dentro del grupo puede considerarse como un elemento aislado.