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Wave load formulae for prediction of wave-induced forces on a slender pile within pile groups

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ABSTRACT

Pile-supported structures commonly found in both offshore (e.g. offshore oil and gas platforms) and coastal environments (e.g. sea bridges, piers and jetties) are generally built by means of a group of piles in different arrangements. The correct prediction of the wave loading of closely-spaced piles of these structures is vital for both safety and economical viewpoints. Unlike single isolated piles, where a large number of studies are available together with the well-known Morison equation which is still widely applied for the calculation of wave-induced force, less research studies have been made on wave-pile group interactions. In fact, no reliable wave load formula is yet available for the prediction of wave-induced forces on a slender pile, for which the pile diameter (D) is generally less than about 0.2 times the wave length (L), within a pile group.

In this study, new wave load formulae for the prediction of wave-induced force on a slender pile in pile groups with different arrangements are developed using a series of laboratory data obtained from systematic model tests conducted in the 2 m-wide wave flume of Leichtweiss-Institute for Hydraulic Engineering and Water Resources (LWI) in Braunschweig, Germany. For the analysis of the laboratory data and the development of the new prediction formulae, an artificial intelligence (AI)-based computational tool, named "*hybrid M5MT-GP model*", is implemented. The new hybrid model and the new wave load formulae allow us to systematically assess 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 $K_G = 1$ where there is no interference effect between neighbouring piles and piles in the group can be treated as a single isolated pile. The accuracy of the new formulae in predicting pile group effect K_G is confirmed by the statistical indicators using agreement index I_a, correlation coefficient CC and scatter index SI.

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 exposed to waves, 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 estimated by the commonly applied formulae for a single isolated pile which are generally based on the concept of Morison et al. (1950).

According to the angle of the connecting line of the piles centres relative to the wave direction, pile groups are commonly categorized into three basic arrangements. These three arrangements include (i) tandem, where the angle of the centre connection line of the cylinders relative to the wave direction is 0°, (ii) side by side, where the incident wave direction is orthogonal to the connecting line of the piles located next to each other, and (iii) staggered in which the angle is between 0° and 90°(Fig. 1). In the case of slender piles where both drag and inertia forces induced by highly complex turbulent flow are important, an analytical solution is hardly feasible. 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 laboratory studies have been carried out to investigate the interference effects of neighbouring piles. The methods commonly used in laboratory studies to determine wave loads on a pile group may be classified in two main categories: "wave force coefficient approach" and "wave force approach".

In the former approach, the inertia and drag coefficients (C_M and C_D) are determined based on the knowledge of both flow velocity and acceleration by applying for instance the least square fit. This approach was used for instance by Chakrabarti (1981, 1982), Haritos and Smith (1995), Smith and Haritos (1996, 1997). Using the calculated drag and inertia coefficients, Chakrabarti (1981, 1982) computed maximum

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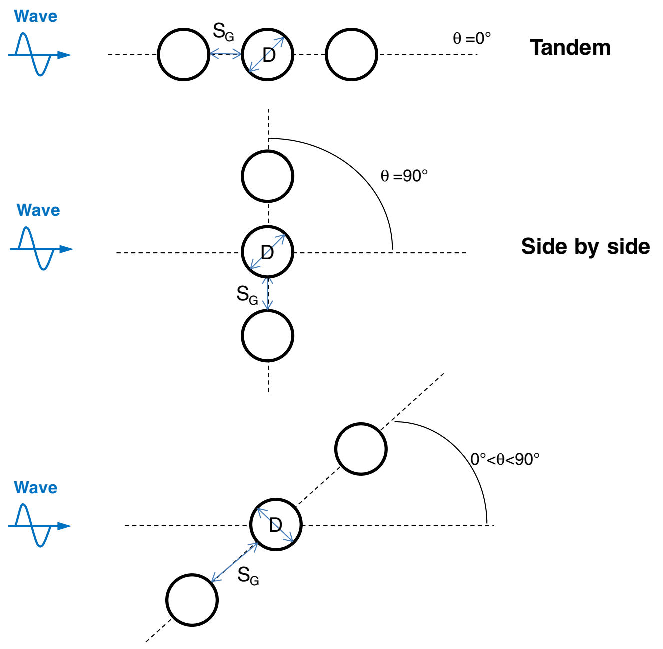

Fig. 1. The three basic pile group arrangements.

wave forces and found a relatively good agreement with measured forces. Smith and Haritos (1996, 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. Using appropriate wave theories, the maximum horizontal wave-induced flow velocity u_{max} was calculated by Chakrabarti (1981, 1982) −0.38 m below still water level at the elevation of the instrumented section of the pile on which the local wave-induced force was measured. Haritos and Smith (1995) as well as Smith and Haritos (1996, 1997) computed u_{max} at the water surface elevation.

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 latter approach, the ratio of wave force on a pile within a group to that on a single isolated pile is determined. This method was applied by Apelt and Piorewicz (1986), 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:

$$K_g = 1.265 - 0.225 ln(S_G/D) \quad \text{for side by side arrangement} \quad (1)$$

$$K_z = 0.836 + 0.141 ln(S_G/D) \quad \text{for tandem arrangement.} \quad (2)$$

In the proposed formulae (Eqs. (1) and (2)), the wave conditions (wave height, period, steepness, etc.) have no influence on interference coefficient K_g and shelter coefficient K_z. For a given pile group arrangement, both coefficients only depend on relative spacing parameter S_G/D which was varied from 0.5 to 3 in the laboratory tests. It was also stated by Mindao et al. (1987) that the interference coefficient K_g and shelter coefficient K_z proposed in Eqs. (1) and (2), are the average of those obtained for the side and middle piles in the pile group arrangements. Li et al. (1993) introduced *significant pile group effect* $K_{G1/3}$ for piles in side by side arrangement exposed to irregular waves. He 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 wave action only.

The interaction of waves and slender piles in different pile group arrangements was also studied by means of extensive large-scale laboratory tests performed in the Large Wave Flume (GWK). A single isolated pile and 14 pile group configurations including side by side, tandem and staggered arrangements with gaps of up to three times the pile diameter ($1 \le S_G/D \le 3$) were tested. The results were analysed by Sparboom et al. (2006), Sparboom and Oumeraci (2006), Hildebrandt et al. (2008), Bonakdar and Oumeraci (2012, 2014) and Bonakdar (2014). Some of the general conclusions drawn from these analyses are:

(i) Pile group effect increases by decreasing the gap between the piles in side by side arrangement,
(ii) The amplification of the wave load on the middle pile in side by side arrangement is more noticeable than the side pile due to the influence of two neighbouring piles from both sides,
(iii) For the tested regular waves ($5 < KC < 38$), the resulting wave load on the middle pile in side by side arrangement increases up to 60% in comparison with that on the single isolated pile. For this pile group arrangement, pile group effect becomes negligible for $S_G/D = 3$ and all piles behave like a single isolated pile in terms of the wave load,
(iv) For tandem arrangement with $S_G/D = 1$, which is the smallest relative spacing tested in GWK, no significant sheltering effect was observed for the tested regular waves ($5 < KC < 38$).

In addition to the aforementioned general outcomes, some of the main limitations of the GWK tests which were identified may be summarized as follows:

(i) Pile group configurations with smaller relative spacing of $S_G/D < 1$, where higher amplification and reduction of wave loads on piles are expected, were not tested,
(ii) The tested wave conditions only cover a small range of relative water depth h/L located in the transition zone ($h/L = 0.084$–0.197). Therefore, the shallow and deep water conditions were not investigated. Moreover, considering the tested KC number values ($5 < KC < 38$), the dominant drag regime and the dominant inertia regime were not fully covered,
(iii) Values of the KC number and Reynolds number ($Re = u_{max}D/\nu$), where ν is Kinematic viscosity, change from one section of the pile to another as a result of the variation of the flow velocity with depth. Only the total wave-induced moment on the instrumented pile was measured meaning that the flow velocity was averaged over the water depth,
(iv) Cantilever piles (truncated with lower end far from the bottom of the flume) were used in the GWK model set-up. This might result in unrealistic flow behaviour around the group of pile due to the flow separation at the lower end (a more detailed discussion is given in Bonakdar, 2014).

Overall, the following knowledge gaps and limitations of the previous studies were identified: (i) the lack of deeper understanding of the processes associated with wave-pile group interaction, (ii) the lack of reliable wave load formulae for the prediction of wave-induced forces on a slender pile within other neighbouring piles in different