A NEW METHODOLOGY TO CALCULATE WAVE-INDUCED FORCES ON STRUCTURES UNDER BREAKING AND NON-BREAKING WAVES

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Abstract

A new methodology is proposed to calculate wave-induced forces under breaking and non-breaking wave conditions. The range of applicability is restricted to slender maritime structures, such as bridge piers. The new methodology combines the SWASH phase-resolving and multi-layered wave model with a semi-empirical formulation. This combination provides the envelope of the vertical distribution of both non-impulsive and impulsive maximum pressures. To assess this new methodology, two sets of available laboratory measurements were used. In general, the comparison shows the proposed methodology can predict impulsive wave pressures to within ±25% of the measured values. This new methodology can be useful to provide wave-induced forces for structural design, both under breaking and non-breaking wave conditions, at an effective time and cost to be used by engineers at preliminary design stages. Current limitations, which can constitute further research studies, are also highlighted.

Introduction and scope

Maritime structures located in shallow, intermediate or deep-water depths are subjected to hydrodynamic loading promoted by wind-generated waves. For maritime structures located in deep-water depths, such as offshore oil platforms, the analytical design methods of hydrodynamic loads are relatively well understood (Sarpkaya and Isaacson, 1981). When these structures are in intermediate or shallow water depths, hydrodynamic loads are associated with more complex phenomena, such as highly nonlinear waves and wave breaking, which makes analytical design methods less reliable. In these cases, Computational Fluid Dynamic (CFD) models that can simulate wave breaking are required. However, CFD models require high-performance computational resources.

The focus is on the hydrodynamic loads promoted by wind-generated waves in intermediate to shallow water depths that maritime structures can be subjected to during their lifetime. We restrict ourselves to slender structures, in which the ratio between the diameter (D) and the incident wavelength (L) is much smaller than one (i.e., $D/L < 0.05$). There is particularly interested in the hydrodynamic loads under breaking conditions. In that situation, air entrainment due to wave breaking of wind-generated waves against slender structures promote very large pressures in a very short time that need to be accounted for in the design.

A typical maritime structure of the environmental conditions above described is a bridge, connecting land to an offshore harbour, that is supported by a series of concrete or steel piers.

Background

Non-breaking wave forces on slender structures

Following CEM VI-5-3, analytical design methods follow the Morison *et al.* (1950) equation for the force per unit length of the pile:

$$f(z) = f_D(z) + f_i(z) = C_D \frac{1}{2} \rho D u(z)|u(z)| + C_M \rho \frac{\pi D^2}{4} \frac{du(z)}{dt} \tag{1}$$

where f_D is the drag force, f_i is the inertial force, ρ is the mass density of the fluid, D is the pile diameter, u is the horizontal water particle velocity, C_D is the drag coefficient and C_M is the inertia coefficient. The latter two coefficients are obtained based on physical experiments. Design graphics are available in CEM IV-5-3 to calculate such coefficients based on nondimensional variables. Analytical design methods based on (1) usually rely on linear wave theory. The vertical integration of (1) gives the total force applied on a pile under non-breaking waves.

Breaking wave forces on slender structures

Under breaking waves, especially plunging breakers, very large impact forces can occur on slender structures. These impact forces are commonly referred as impact, impulsive or slamming forces. The SPM (1984) suggests multiplying the depth-integrated drag force (F_D) in (1) by 2.5 to account with the impulsive force. Following Wienke and Oumeraci (2005), the maximum impulsive force (f_s), which occurs at t = 0 s

$$f_s = \lambda \eta_b C_s \rho \frac{D}{2} C^2 \quad (2)$$

where λ is the curling factor, η_b is the sea-surface elevation associated with the breaking wave height H_b, C_s is the slamming factor and C is the breaking wave celerity. Figure 1 depicts a schematic diagram. The product between λ and η_b is the area of impact. In general, the impulsive force is considered to be depth-independent over the area of impact. C_s values available in the literature range between 3.14 and 6.28. Like non-breaking wave forces, a wave theory is used to obtain the wave characteristics (see Paulsen *et al.* 2019 for a recent update on impulsive wave forces on slender maritime structures).

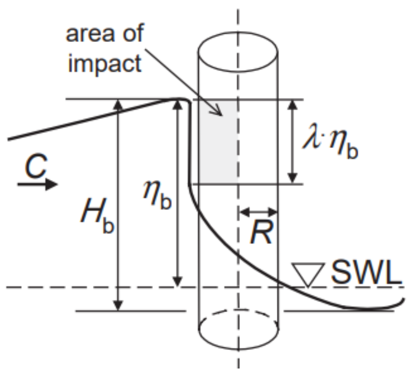


Figure 1 – Schematic diagram of the parameters to consider on a slender structure under breaking wave conditions (Wienke and Oumeraci, 2005).

CFD numerical modelling

Besides analytical design methods, CFD numerical models are often used to calculate wave forces on slender maritime structures, under both breaking and non-breaking waves. As an example, Kamath *et al.* (2016) applied the open-source CFD model REEF3D to simulate plunging wave forces on a vertical cylinder. The comparison between REEF3D and large-scale laboratory data from Wienke and Oumeraci (2005) suggests a very good matching at the maximum impulsive wave force. Disadvantages of CFD numerical models include the computational resources required to perform simulations, the inability to simulate long wave time series, which precludes the assessment of an irregular sea state, and the required expertise to conduct CFD modelling.

New methodology

In this study, a new methodology to calculate wave forces on slender maritime structures is proposed to achieve two objectives: 1) to be more generally applicable than analytical design methods that often rely on linear wave theory; and 2) to be much less computationally consuming than CFD modelling. Overall, this new methodology can be useful to engineers at preliminary design stages.

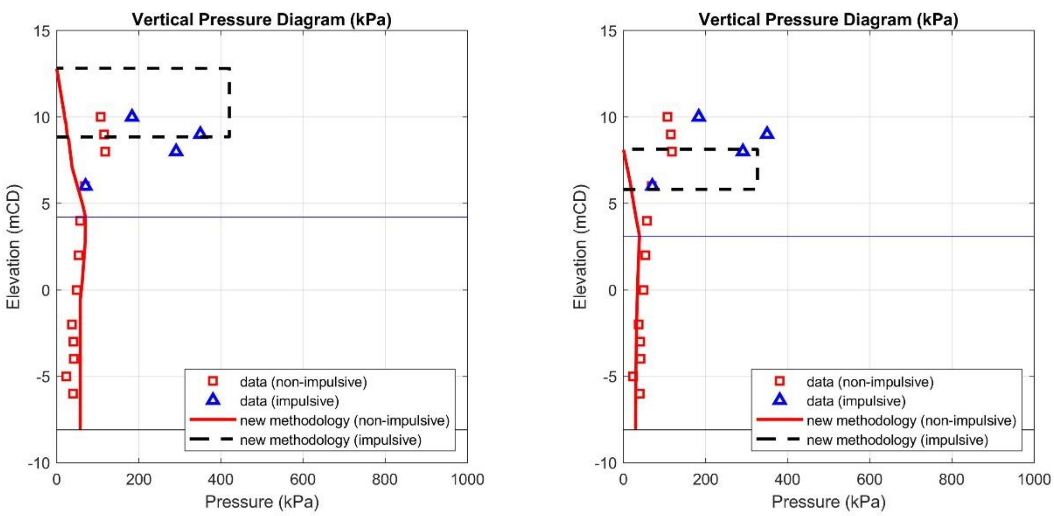
The new methodology combines a phase-resolving numerical model and the semi-empirical equation (2). Here, we used the multi-layer SWASH model with a 2DV approach to provide pressure values over the vertical and values of η_b near the structure. Values of λ and C_s were set to 0.46 and 6.28, respectively. Wave celerity was calculated based on solitary wave theory. This new methodology was inspired by the work developed by van Maris (2018), which was restricted to non-breaking waves against vertical walls.

By using SWASH, a depth-variable pressure time series can be obtained for an irregular sea state composed of several waves (e.g., 1000 waves). The methodology is as follows. First, an envelope of the maximum pressure values along the vertical is calculated. These pressure values are associated with non-breaking waves. Second, the η_b associated with the largest previously determined pressure value is obtained (typically at 1 m to 2 m from the structure). Then, (2) is used to determine the slamming pressure diagram (see Figure 2).

Results and discussion

In this study, two sets of available laboratory experiments performed by Artelia were used on a 1:22 scale to verify the new methodology. An acrylic cylinder was instrumented with 13 pressure sensors displaced along the vertical in a long wave flume. Pressure time series were recorded at 1000 Hz to accurately capture impulsive pressure values that occur in very short time scale (< 0.5 s in prototype). Artelia split the results into non-impulsive and impulsive pressure values (Figure 2). Note the latter values usually take place at high elevations, similar to Figure 1. The two different cases are associated with two distinct design wave conditions and associated water depths.

For the first design wave condition (Figure 2a), the new methodology is able to accurately match the laboratory non-impulsive wave pressure values up to mean water level. The maximum impulsive wave pressure recorded in the laboratory (~350 kPa) is slightly overestimated by the new methodology (~425 kPa). Moreover, the new methodology predicts the impulsive wave pressure at elevations higher than those measured in the laboratory experiments.



a) b)

Figure 2. Comparison between the new methodology (lines) and Artelia laboratory experiments

(markers) for non-impulsive (red) and impulsive (blue/black) pressures. Pressure values are the envelope of maximum pressures over the time series at each elevation.

For the second design wave condition (Figure 2b), the new methodology can also match the laboratory non-impulsive wave pressure values up to slightly above mean water level. The maximum impulsive wave pressure recorded in the laboratory (~380 kPa) is slightly underestimated by the new methodology (~350 kPa). In this case, the new methodology slightly underestimates the elevation at which the impulsive wave pressure takes place.

Conclusions and recommendations

Here, a new methodology was presented to calculate wave forces on maritime structures where the wave loading under breaking and non-breaking waves occurs on slender elements, such as bridge piers. The methodology combines the multi-layer and phase-resolving SWASH numerical model with a semi-empirical equation. A first comparison against available laboratory experiments provides a good matching, especially for impulsive wave pressures.

Advantages of this new methodology when compared with analytical design methods are the simulation of irregular sea states and the inherently simulation of underwater bathymetric features. When compared with CFD models, a key advantage is the computational demand which is compatible with the time requirements associated with design projects in practice.

Current limitations that can constitute future research avenues include a detailed analysis on the use of a 2DV approach to predict a 3D phenomenon, the availability of laboratory and field measurements of impulsive pressures on bridge piers and pressure variation along the pier cross-section. Moreover, a tracking algorithm of the wave breaking phenomenon will constitute a good update to this newly proposed methodology.

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