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Verfügbar unter/Available at: <https://hdl.handle.net/20.500.11970/106633>

Vorgeschlagene Zitierweise/Suggested citation:

Tomás, Antonio; Álvarez de Eulate, María F.; Barajas, Gabriel; Lara, Javier L.; Losada, Inigo J.; Rodriguez de Segovia, María Fátima; Esteban, Francisco (2019): A New Methodology to Simulate Three-Dimensional Hydraulic Loads on a Vertical Breakwater along its Life Cycle. In: Goseberg, Nils; Schlurmann, Torsten (Hg.): Coastal Structures 2019. Karlsruhe: Bundesanstalt für Wasserbau. S. 222-233. https://doi.org/10.18451/978-3-939230-64-9_023.

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A New Methodology to Simulate Three-Dimensional Hydraulic Loads on a Vertical Breakwater along its Life Cycle

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Abstract: A new methodology has been defined to calculate three-dimensional loads (forces and moments) and hydraulic stability (sliding and overturning) on concrete caissons all along construction stages of their life cycle, from isolated caissons to the final operation phase. The study of wave loading on the caisson has been simulated using a coupling of two CFD (Computational Fluid Dynamics) models: the two-dimensional model IH2VOF and the three-dimensional model IHFOAM. In order to take into account the wave climate variability and uncertainties associated with all processes involved, the Monte-Carlo statistical technique has been used with a hybrid numerical simulation methodology. This new methodology allows for numerical optimization of computational costs and provides reliable results, because of the large number of cases simulated. The application of this methodology in a real study case is shown in this paper: the main vertical breakwater of Granadilla Port (Tenerife, Spain).

Keywords: Wave-structure interactions, Computational Fluid Dynamics, Hydraulic stability, Life Cycle, Monte-Carlo.

1 Introduction

1.1 General context

Methods used for the study of coastal structures have evolved in the last decade after the incorporation of advanced numerical tools. The development of computational techniques and the evolution of new and more efficient computing resources have provided a complementary use of these tools as an alternative to traditional methods: dimensional analysis and physical modeling in laboratory. In parallel, in the last years, the use of reinforced concrete caissons in vertical breakwaters has been generalized due to reductions of construction schedules and costs.

Computational Fluid Dynamics (CFD) is one of the most widely used technique in coastal engineering to determine wave loading. It is the most suitable approach due to its ability, versatility and accuracy to solve complex physical processes. The use of CFD models in other fields of engineering is quite common to optimize designs and construction methods. However its use in coastal engineering has not been fully incorporated into design methodologies yet, although there are already CFD models in the literature that reproduce reliable wave-structure interactions, such as three-dimensional effects and non-conventional structures (Higuera et al., 2013, Park et al., 2018, Qu et al., 2019, González-Cao et al., 2019).

Furthermore, in the design process of a breakwater there is uncertainty in the results obtained, not only due to the used tools, but also because of the methodologies, the geometric and resistance characterization of each of the breakwater elements and construction stages, changes in bathymetry, the stochastic behavior of wave climate incident to the structure, climate change effects, etc. All these uncertainties must be taken into account, since the life cycle of this type of structures is usually of

several decades. Therefore, it is almost always necessary to use probabilistic methodologies in the design of breakwaters.

Currently, there are no probabilistic methodologies using efficiently CFD models to characterize the three-dimensional hydraulic loads on a vertical breakwater along its life cycle, because of the high amount of computational time required. For coastal engineering applications (solving coastal processes) there is a group of methodologies which combines numerical models (dynamic tools) with mathematical or statistical tools to reduce the computational effort (Camus et al., 2011b, Herman et al., 2009, Jihee and Kyung-Duck, 2018, Rueda et al., 2019). They are known as hybrid methodologies. For coastal structures, a hybrid methodology has been adopted for the calculation of wave loads on vertical breakwaters (Guanche et al., 2013), based on the selection of a number of sea states, the calculation of the hydraulic stability of the breakwater and finally their reconstruction using a statistical technique. However, in this methodology, the calculation of the hydraulic stability is based on semi-empirical formulae, not CFD models.

1.2 Objectives

The main objective of the present work is the definition of a methodology to determine the maximum three-dimensional wave loading and the hydraulic stability on reinforced concrete caissons along the different construction stages of their life cycle. On these bases, the failure probability of the hydraulic stability along the life cycle of a vertical breakwater will be calculated.

Wave loadings will be simulated using two-dimensional and three-dimensional CFD models, and will be compared with the state-of-the-art semi-empirical formulae results.

The methodology to be developed will also be able to assess the uncertainty on results, taking into account uncertainties on caisson geometry, wave loads calculation, local wave climate and climate change effects.

The methodology will be applied to a real study case.

1.3 Document structure

This paper is organized as follows: an introduction to the problem and the definition of the objectives are explained in section 1. In section 2, the study case is presented. The proposed methodology is described in section 3. In section 4, results obtained by the application of the methodology to a real study case are presented. The conclusions of the study are exposed in section 5. Finally, a discussion based on results obtained and a possible optimization procedure is proposed in section 6.

2 Study case

The real study case, in which the new methodology is applied, is the main vertical breakwater of Granadilla Port (Tenerife, Spain), see location in figure 1. The main vertical breakwater is 1.5 km long with a maximum depth of 50 m. It is composed by reinforced concrete caissons, anchored at -24 m depth, with a crest at +11 m elevation (see F3 in figure 2). The caisson type to be studied has a length of 56.6 m, a beam of 20.85 m and a depth of 27 m.

2.1 Wave climate

Wave climate incident to the breakwater is defined thanks to IHCantabria's global databases (www.ihcantabria.com). Based on Global Ocean Waves (GOW, Reguero et al., 2012) calibrated hindcast, propagated wave data is characterized by using Downscaled Ocean Waves (DOW, Camus et al., 2013) hindcast. Figure 1 shows the directional extreme wave climate characterization (H_s , significant wave height and T_p , peak wave period) in front of the breakwater.

Local sea level is obtained through the composition of the Astronomical Tide (AT), the Storm Surge (SS) and the Sea Level Rise (SLR). Astronomical tide is characterized based on Global Ocean Tide (GOT) database generated by TPXO global model (Egbert and Erofeeva, 2002). Storm surge is characterized based on Global Ocean Surge (GOS, Cid et al., 2014) hindcast. Sea level rise evolution is obtained from RCP 8.5 (Representative Concentration Pathway 8.5), whose mean SLR value is 0.29

m for the period between 2046-2065 years (Wong et al. 2014). This value is regionalized for the study case following the spatial pattern provided in Slangen et al. (2014).

Note that for all wave climate variables (Hs, Tp, AT, SS & SLR) used, both variability and also uncertainty (see example of mean and standard deviation of Hs and Tp extreme values in figure 1) are characterized.

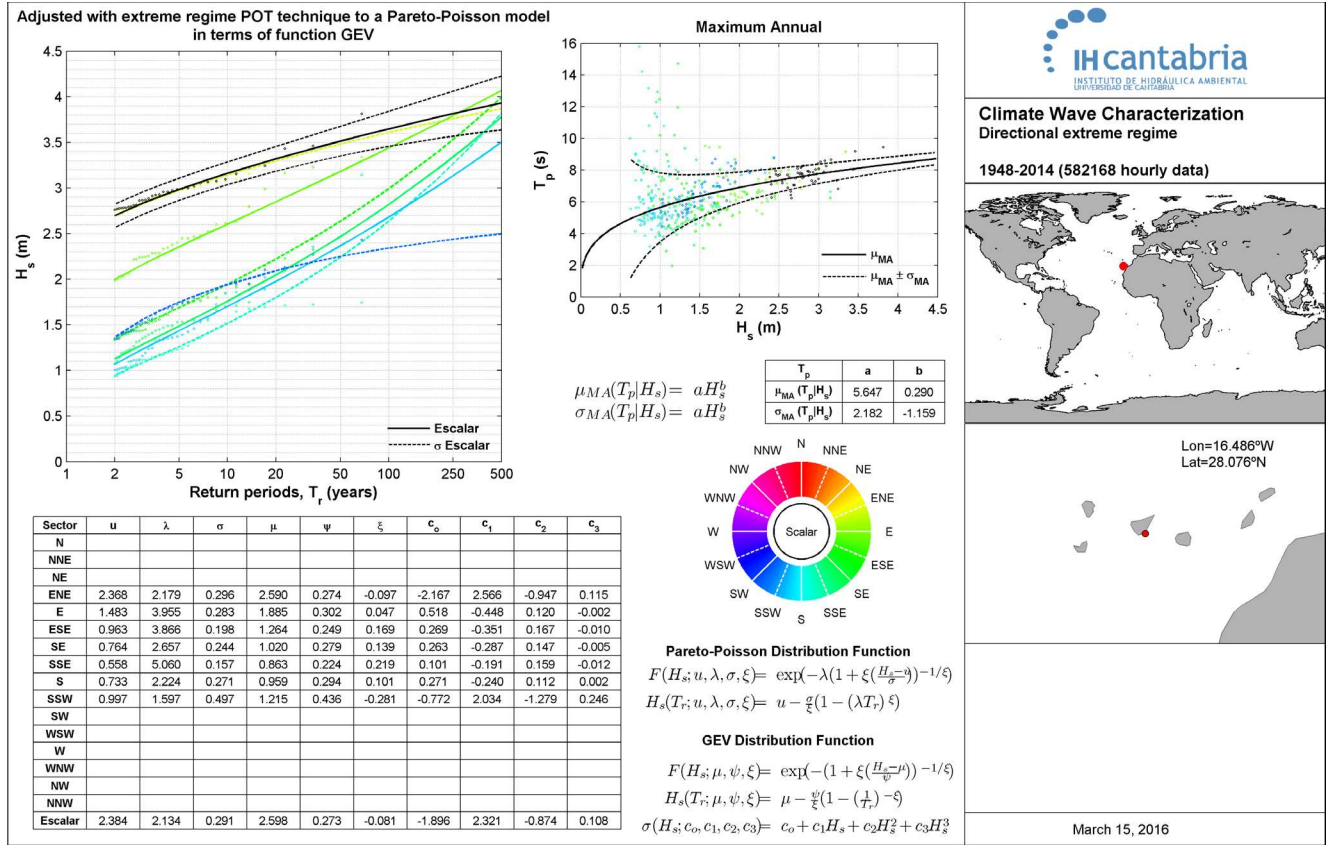


Fig. 1. Extreme wave climate characterization in front of Granadilla Port (Tenerife, Spain).

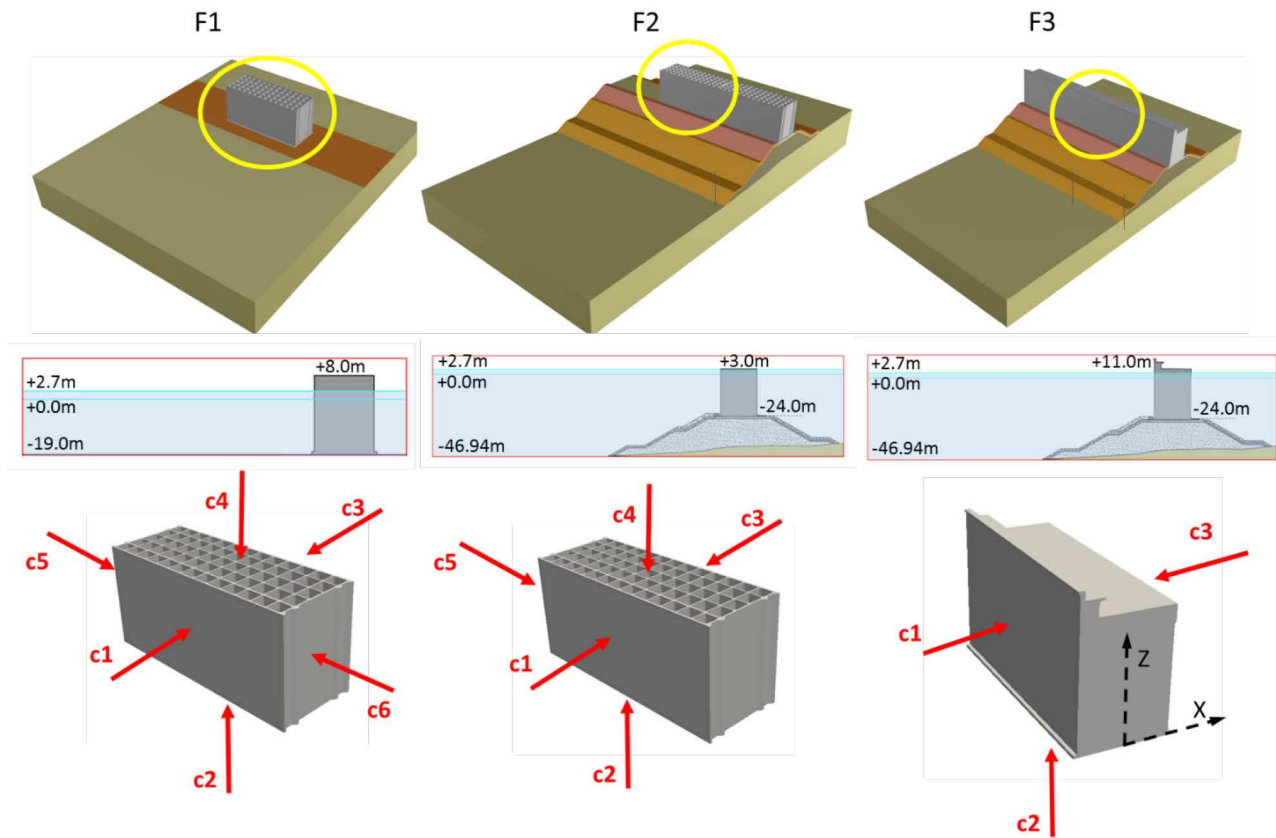


Fig. 2. Geometric (upper panel) and load (lower panel) schemes of three different construction stages of the Granadilla vertical breakwater (F1, F2 & F3). F1: initial stocking of isolated caissons. F2: temporary head of the breakwater (caissons without superstructure). F3: operation phase including sea level rise due to climate change.

2.2 Geometrical configuration

There are different construction stages along the life cycle of a caisson during the construction of a vertical breakwater. Three different geometrical construction stages are defined for Granadilla vertical breakwater (see figure 2):

- **F1: initial stocking of isolated caissons.** After the construction of the caisson in a floating dock, and before the anchoring of the caisson in its final position, it is usual to anchor the caisson in a temporal position, filling the cells with water.
- **F2: temporary head of the breakwater.** After stage F1, the caisson is anchored in its final position, filling the cells with sand. Before the construction of the superstructure, the worst stability situation occurs when the caisson works as the temporary head of the breakwater.
- **F3: operation phase.** After stage F2, remaining caissons are anchored, and the superstructure and crest are built. This is the final layout, in which the breakwater starts operating and remains during its useful life.

The different construction stages configurations result in changes in the caisson weight (see table 1).

Tab. 1. Caisson weight and Center of Gravity (CG) position of three different construction stages of the Granadilla vertical breakwater (F1, F2 & F3)

	F1	F2	F3
Weight (kg) *	36185850	67973680	76030350
Xcg (m)	0.00	0.00	-0.26
Zcg (m)	11.61	13.41	15.05

* Variation coefficient of 5% is adopted

2.3 Design criteria

Design basis are defined according to ROM standards (ROM 0.0-01, ROM 1.0-09) and construction constraints of Granadilla vertical breakwater.

Useful life (V) is established for each construction stage:

- F1: $V_1 = 1$ year
- F2: $V_2 = 1$ year
- F3: $V_3 = 50$ years (including sea level rise due to climate change)

The maximum joint probability of failure in the useful life is established in 10%.

For the three different construction stages, the same failure modes are defined. Only the hydraulic stability of the caisson is studied. The failure modes are defined as the sliding and overturning of the caisson, both towards seaside and leeside; they are evaluated through hydraulic safety factors (SF) for each construction stage:

- F1: Failure, if any $SF \leq 1.0$.
- F2: Failure, if any $SF \leq 1.5$.
- F3: Failure, if any $SF \leq 1.5$.

In the definition of safety factor, a friction coefficient of 0.65 (between caisson and foundation) is adopted, with a variation coefficient of 10%.

3 Overall methodology

In order to take into account the wave climate variability and uncertainties associated with all processes involved in the calculation of the hydraulic stability on concrete caissons during all construction stages of their life cycle, the Monte-Carlo statistical technique has been used with a hybrid numerical simulation methodology to verify the design criteria established for the vertical breakwater.

The hybrid methodology is based on a definition of a meta-model to downscale wave dynamics to evaluate three-dimensional hydraulic loads on the caisson. The meta-model is defined similar to Guanche et al (2013) but improving the calculation of wave loads by using two-dimensional (2D) and three-dimensional (3D) CFD models, instead of traditional semi-empirical formulae (SE Formulae). In order to compare SE Formulae, CFD 2D and CFD 3D results, three different meta-models are defined.

The random simulation methodology, for each of the N simulations of life cycle with $V=V_1+V_2+V_3$ years, follows the schedule outlined in figure 3.

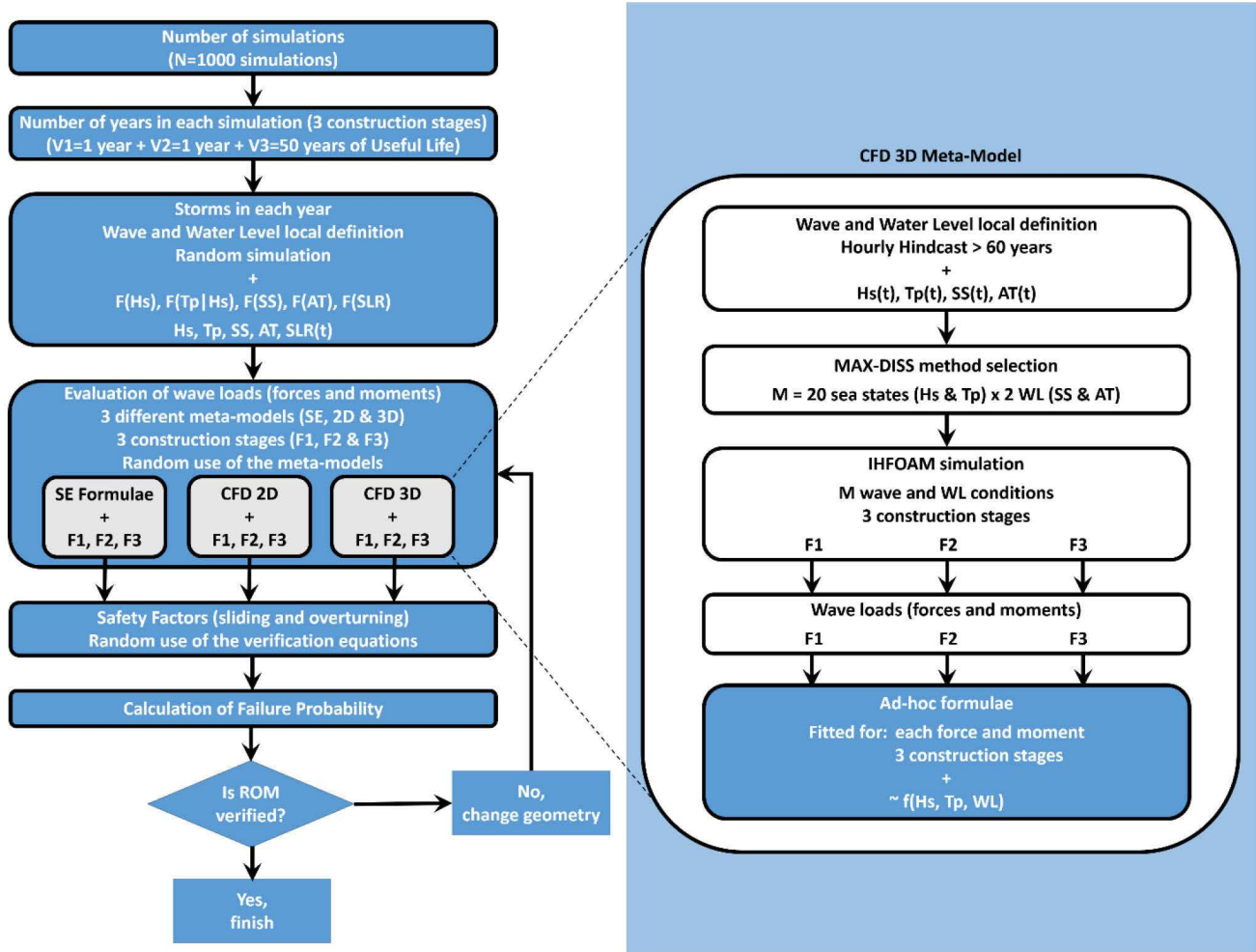


Fig. 3. Left panel: Overall methodology of the simulation (and optimization up to ROM verification) of the hydraulic stability of a vertical breakwater along its life cycle. It takes into account three different construction stages (F1, F2 & F3) and three different meta-models or approaches to evaluate wave loads (SE Formulae, CFD 2D and CFD 3D). Right panel: Methodology of the CFD 3D meta-model.

3.1 Meta-models definition

As mentioned before, three different meta-models or approaches to evaluate wave loads (SE Formulae, CFD 2D & CFD 3D) are defined. In addition, each meta-model has three different fits, one for each construction stage (F1, F2 & F3).

SE Formulae meta-model uses the classical two-dimensional tools to calculate wave loads on the caisson, as a function of wave and water level conditions. The maximum wave loads (or crest loads) are obtained by using Goda (1985) and Takahashi et al. (1994) semi-empirical formulae. On the other hand, the minimum wave loads (or trough loads) are obtained by using Sainflou (1928) semi-empirical formulae. Both calculations incorporate the bias and uncertainties determined in PROVERBS (2001).

CFD meta-models use the hybrid methodology to calculate wave loads on the caisson (see example of the CFD 3D meta-model methodology in right panel of figure 3). Hybrid modelling departs from a selection of representative number M of sea states from the local wave hindcasts; the selection is made with the Max-Diss technique (Camus et al., 2011a). In this case, a number WL of water levels, for each sea state, are selected too. These $M \times WL$ hourly wave and sea level conditions are numerical modeled with selected CFD models. Based on the wave loads obtained by CFD numerical simulations (forces and moments, maximum and minimum, seaside and leeward), ad-hoc formulae for each construction stage are fitted. Ad-hoc formulae are linear fit that adjust SE Formulae with CFD results, including the uncertainty of the results obtained by the numerical simulations (see example of CFD 2D fits in figure 6). This approach makes possible to obtain quickly CFD wave loads for any wave and sea level conditions.

CFD 2D meta-model uses two-dimensional IH2VOF model (<http://ih2vof.ihcantabria.com>, Lara et al., 2008, Guanche et al., 2009). IH2VOF solves the two-dimensional wave flow for domains in a

coupled Navier Stokes-type equation system, at the clear-fluid region (outside the porous media) and inside the porous media by the resolution of the Volume-Averaged Reynolds Averaged Navier-Stokes (VARANS) equations. Turbulence is modelled using a $k-\epsilon$ model for both the clear-fluid region and the porous media region. IH2VOF is one of the most advanced RANS models thanks to its capabilities, robustness and extensive validation for both surf zone hydrodynamics and the stability and functionality of conventional or non-conventional coastal structures. Realistic wave generation, second order generation and active wave absorption are some features included in the model.

Finally, CFD 3D meta-model uses three-dimensional IHFOAM model (<http://ihfoam.ihcantabria.com>, Higuera et al., 2014a Higuera et al., 2014b). IHFOAM is a newly developed three-dimensional numerical two-phase flow solver specially designed to simulate coastal, offshore and hydraulic engineering processes. Its core is based on OpenFOAM® ESI-Group (<https://www.openfoam.com/>), a very advanced multiphysics model, widely used in the industry. What makes IHFOAM different from the rest of solvers is a wide collection of boundary conditions which handle wave generation and active absorption at the boundaries. These specific boundary conditions allow to generate any type of wave in a 3D domain, from regular waves to complex, real and fully 3D irregular directional sea states. IHFOAM can also solve two-phase flows within porous media by means of the VARANS equations.

The objective at this step of the methodology is the calculation of the wave loading on the caisson using the CFD 3D model. Taking into account that the computational cost of 3D simulations is very high, a coupling methodology between 2D and 3D CFD models has been applied. This methodology consists in simulating with CFD 3D only the critical wave package of each sea state. This critical wave package is previously selected as the one that provides the minimum safety factor of an hourly sea state simulated with CFD 2D model. Regarding the computational domains of 2D and 3D simulations, figure 4 shows a diagram of the coupling of these two CFD models. To do the coupling between the models, a free surface gauge at the coupling position (red gauge) is defined. Then, the free surface and velocities along the water column for the critical wave package are used as the forcing for CFD 3D simulations.

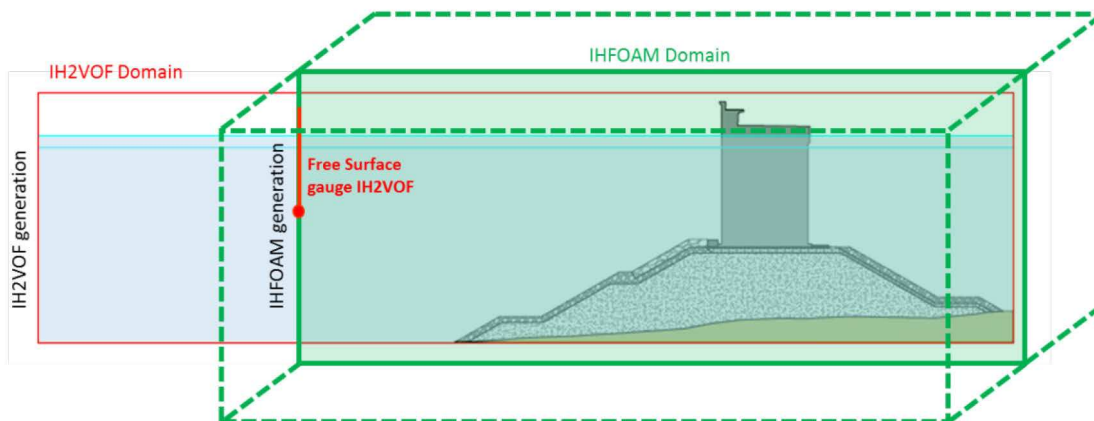


Fig. 4. IH2VOF (CFD 2D) and IHFOAM (CFD 3D) model nesting sketch.

4 Results

The methodology previously defined was applied to the real study case of the main vertical breakwater of Granadilla Port (Tenerife, Spain). $N=1000$ stochastic simulation of $V=52$ years life cycles were simulated using the Monte-Carlo technique to characterize the hydraulic stability of the caisson along the three construction stages of its life cycle (F1, F2 & F3), evaluating wave loads by using three different meta-models (SE Formulae, CFD 2D & CFD 3D). Finally, probability distribution of caisson safety factors, for each construction stage and meta-model, were obtained.

Note that the CFD meta-models were fitted with $M=20$ sea states, $SL=2$ sea levels (High Tide and Low Tide) and 3 breakwater configurations; which results in 120 CFD 2D simulations and other 120 CFD 3D simulations. Figure 5 shows an example of CFD 3D results for F2 construction stage.

Based on CFD results (forces and moments, maximum and minimum, seaside and leeside), ad-hoc formulae adjusting SE Formulae with CFD results (2D and 3D) for each construction stage (F1, F2 &

F3) were fitted. Figure 6 shows an example of CFD 2D ad-hoc formulae linear fit for maximum and minimum horizontal force for F1. In figure 6 a good linear fit is observed and a general decrease of loads magnitude with respect to the classical semi-empirical formulae (as in all other fits, not shown here).

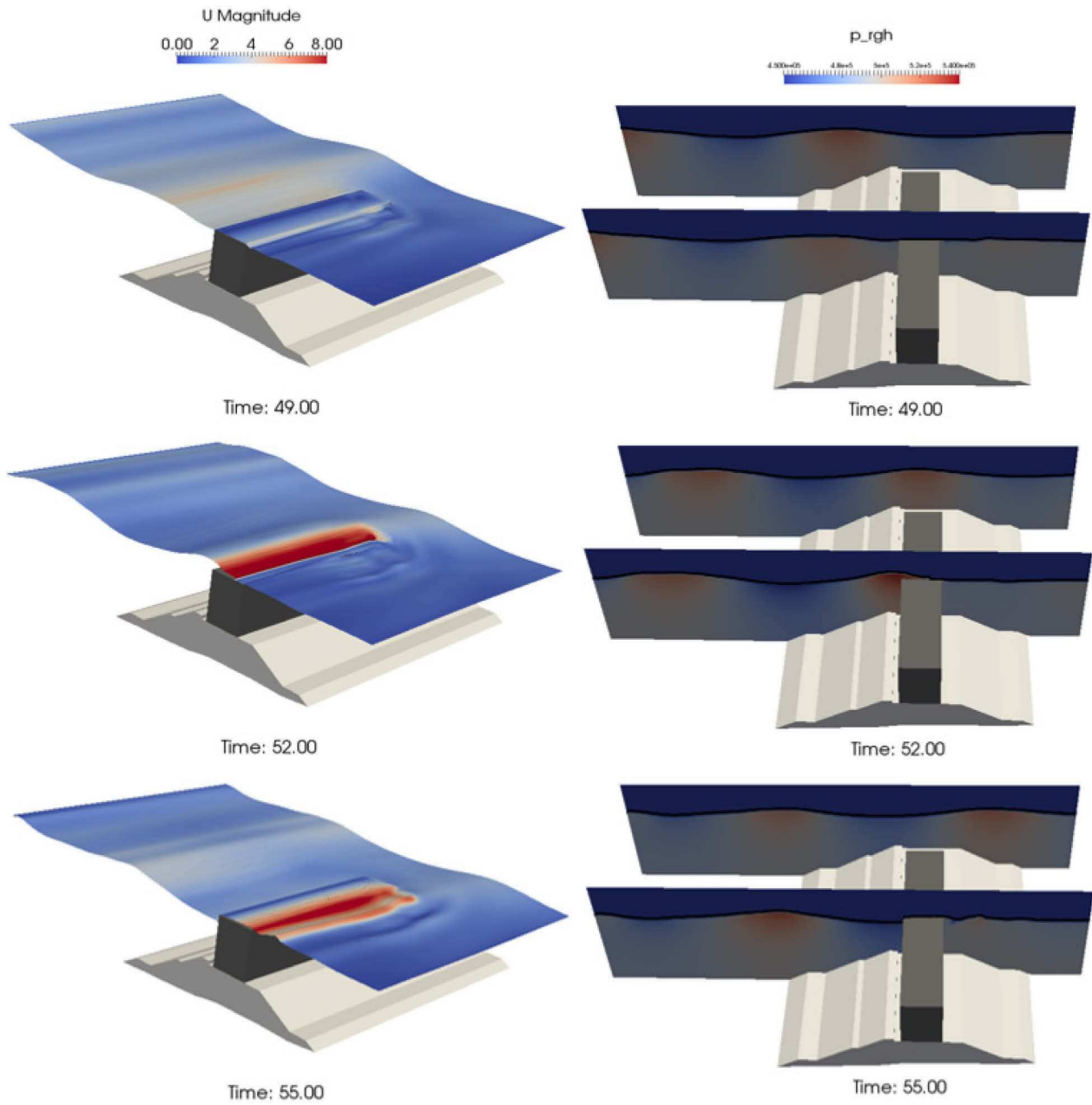


Fig. 5. Snapshots on the free surface of velocity magnitude (left panel) and dynamic pressure (right panel) obtained by IHFOAM for the second construction stage (F2) of the Granadilla vertical breakwater. $H_s = 4.6$ m, $T_p = 9.6$ s, $WL = +2.7$ m (High Tide).

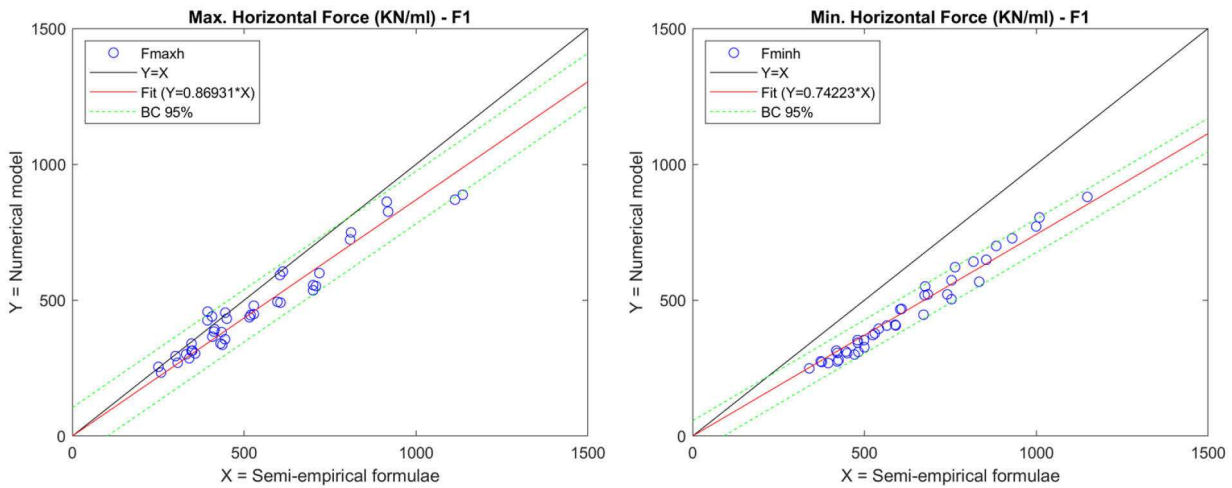


Fig. 6. Maximum (left panel) and minimum (right panel) horizontal dynamic force (c_1 , see figure 2) on the first construction stage (F1) of the caisson. IH2VOF numerical model results versus semi-empirical formulae results.

After the $N=1000$ Monte-Carlo simulations of whole life cycles, probability density function (PDF) of caisson safety factors for each construction stage and meta-model, is obtained (see figure 7); together with the mean and the standard deviation of each PDF (see table 2). It can be seen that the caisson has a significant safety margin (safety factors, $SF > 1.5$) and F2 has the highest SFs. When comparing the three meta-models results, the two CDF models give similar PDFs, but with SFs larger than SE ones. This is due to SE wave loads are larger than CFD ones. Therefore, according to CFD results (which better represent the hydraulic performance of the caissons), these caissons have too large SFs, so they could be optimized to reduce them.

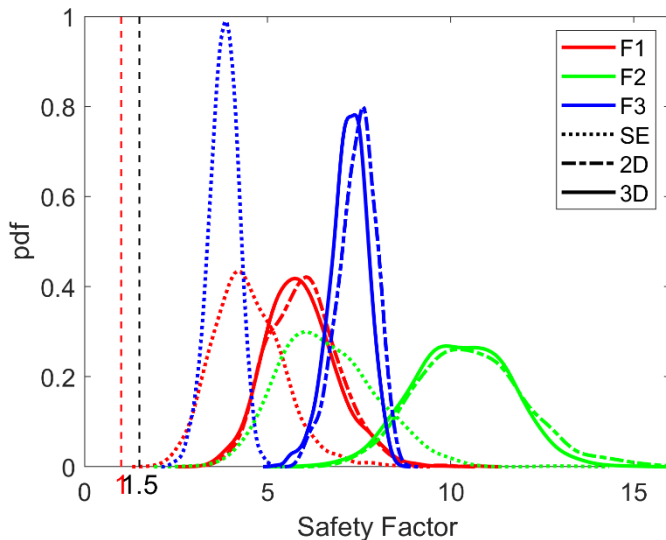


Fig. 7. Probability Density Function of hydraulic Safety Factor (sliding and overturning of caisson) for the three construction stages (F1 in red, F2 in green & F3 in blue) and the three meta-models to evaluate wave loads (SE, 2D & 3D). SE: Semi-Empirical formulae (dot lines). 2D: two-dimensional CFD (dashed-dot lines). 3D: three-dimensional CFD (solid lines). Red dashed line is $SF = 1$ (the equilibrium limit). Black dashed line is $SF = 1.5$ (the established limit).

Tab. 2. Mean and standard deviation of hydraulic Safety Factor PDF for the three construction stages (F1, F2 & F3) and the three meta-models (SE Formulae, CFD 2D & CFD 3D)

Safety Factor	F1		F2		F3	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
SE Formulae	4.48	0.95	6.64	1.31	3.80	0.39
CFD 2D	5.99	0.94	10.5	1.47	7.45	0.51
CFD 3D	5.92	0.97	6	10.3	7.22	0.50
			1			

5 Conclusions

A new methodology has been defined for the calculation of three-dimensional loads (forces and moments) and hydraulic stability (sliding and overturning) on reinforced concrete caissons along all construction stages of their life cycle. This includes from isolated caissons (F1), through temporary head of the breakwater (F2), to the final operation phase (F3). This methodology takes into account uncertainties on caisson geometry, wave loading calculation, local wave climate and climate change effects; and manages all the information by using the Monte-Carlo statistical technique.

The study of the wave loading on the caisson has been analyzed by using three different tools: classical semi-empirical formulae (SE Formulae), the two-dimensional CFD model IH2VOF and the three-dimensional CFD model IHFOAM. In order to compare SE Formulae, CFD 2D and CFD 3D results, three different meta-models have been defined with a hybrid numerical simulation methodology.

In the CFD 3D meta-model, an efficient coupling methodology between the two CFD models (IH2VOF and IHFOAM) has been applied. This coupling method results in a numerical optimization regarding computational costs and provides reliable results.

The application of the methodology has allowed to calculate the probability density functions of the hydraulic stability along the life cycle of a vertical breakwater, for each construction stage and meta-model. This methodology also allows to probabilistically verify the design criteria established for the vertical breakwater.

An application of this methodology has been performed in a real study case, the main vertical breakwater of Granadilla Port (Tenerife, Spain). In this case, it has been observed that if the caissons are designed with classical SE Formulae, the caissons appear to be oversized. However, using CFD models it is possible to reduce the uncertainty and increase the accuracy and reliability of results.

6 Discussions

Based on the methodology and study case above, several Monte-Carlo simulations have been carried out, but now reducing the weight of the caisson. The purpose is to compare the variation in the probability of failure with the reduction in the weight of the caissons, to evaluate the potential capability to optimize the caisson.

In figure 8, changes in the failure probability are shown, and in table 3, values for 10% failure probability are presented. Therefore, from the point of view of its hydraulic stability, it is possible to optimize the geometry of the caisson in order to reduce its weight. The weight of the caisson could be reduced by about 8% (82.5%-74.8%, see table 3), by using CFD tools and the proposed probabilistic methodology. This fact would mean a large reduction in the construction cost of the analyzed breakwater.

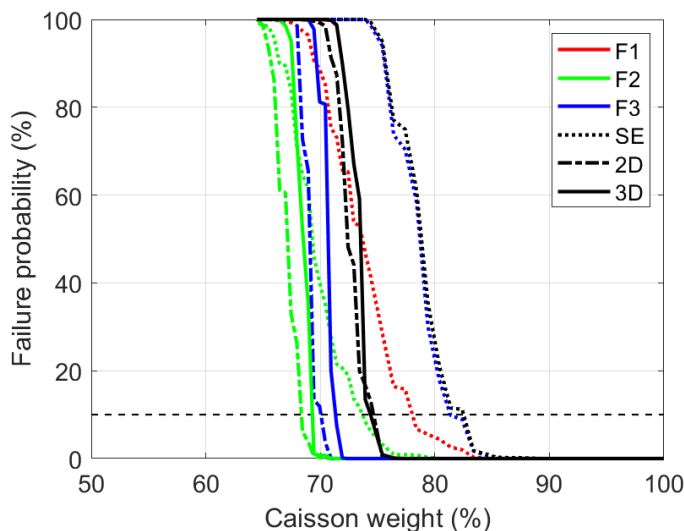


Fig. 8. Failure probability percentage of the caisson hydraulic stability depending on the percentage of caisson weight. Results for three construction stages (F1 in red, F2 in green & F3 in blue) and along the life cycle (black lines), and three meta-models to evaluate wave loads: SE Formulae (dot lines), CFD 2D (dashed-dot lines) and CFD 3D (solid lines). Black dashed line is the 10% failure probability (limit established by ROM).

Tab. 3. Percentage of caisson weight that just reaches a failure probability less than 10%, for the three construction stages (F1, F2 & F3) and the whole life cycle, and the three meta-models (SE Formulae, CFD 2D & CFD 3D)

% Weight for 10% Failure	F1	F2	F3	Total life cycle
SE Formulae	77.9	73.8	81.5	82.5
CFD 2D	74.6	68.0	70.0	74.6
CFD 3D	74.8	68.3	69.1	74.8

Acknowledgments

This work has been part of the research project DOVICAIM (RTC-2014-3077-4), which was financially supported by the Spanish Ministry of Economy, Industry and Competitiveness (MINECO) within the National Program for Research Aimed at the Challenges of Society.

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