

MODELING WAVE-STRUCTURE INTERACTION IN A CHANGING CLIMATE

Stefano De Finis
Docenti Guida: Prof. Giorgio Bellotti – Prof. Claudio Lugni

RESEARCH TOPIC

Coastal areas are great zones of settlement and play a vital role for the wealth of many Countries. The European coastline extends for more than 68.000 km and coastal areas cover about 2.000.000 km². Over the past 50 years, the population living in European coastal municipalities has more than doubled reaching 70.000.000 inhabitants in 2001. The total value of economic assets located within 500 m of the coastline was estimated between 500 € and 1.000.000.000 €.

Sea level rise and more intense storms, waves and surges due to climate change pose a serious threat to large number of people living in those areas. All these phenomena cause a variation of the initial value of the designing parameters for existing coastal structures (e.g. the freeboard R_c or the significant wave height H_{m0}) and can generate conditions much more critical than those assessed before the work construction.

The aim of the present research is to analyse the stresses induced by waves on coastal works, especially expressed in terms of impacts on vertical structures, within a scenario of increasing uncertainty caused by the climate change and the sea level rise, suggesting an adjustment of them where necessary.
The approach used combines physical models with numerical models.

IMPACTS ON A STORMWALL

EXPERIMENTAL CAMPAIGN

Although great efforts have been made in the study of overtopping, still little is known about the post-overtopping phenomena such as the impacts on vertical structures placed at the end of a promenade on a smooth sloping dike.

Two experimental campaigns were carried out in the CIEM of UPC Barcelona (Hydralab Project) and in the wave flume of Ghent University (Van Doorslaer et al. (2017)), in order to determine the impact force $F_{1/250}$ acting on the storm wall.

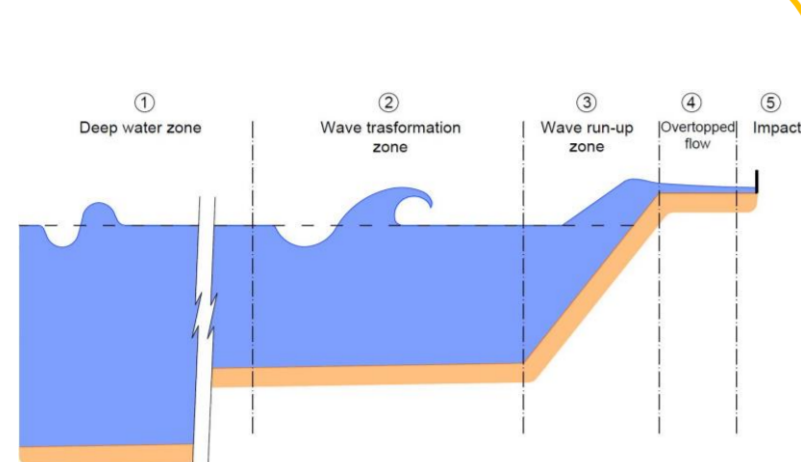


Figure 1 – Evolution from deep water waves to the bore impacting a storm wall

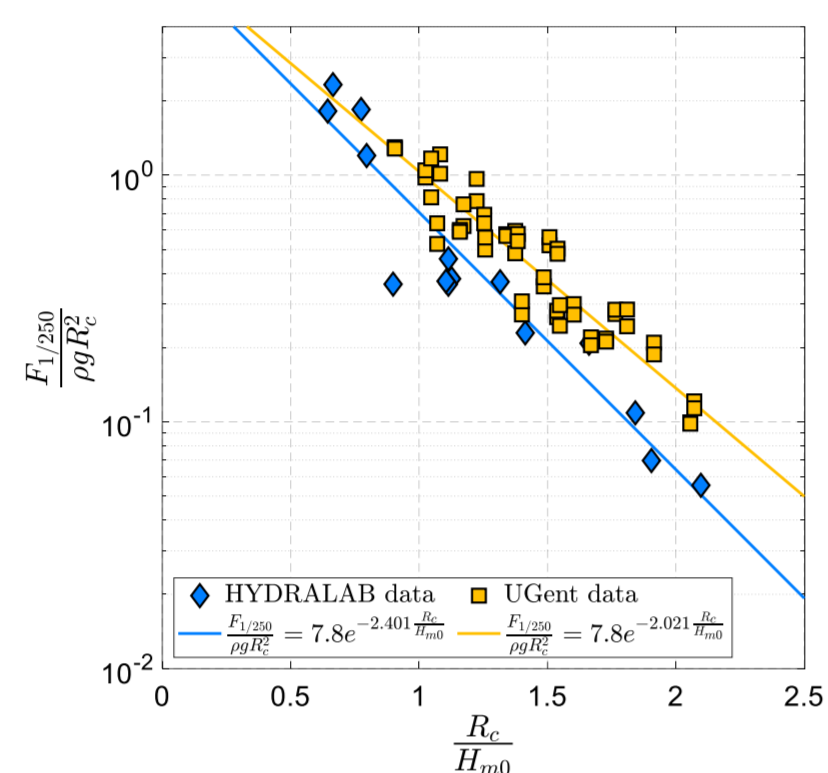


Figure 3 – Experimental results and prediction formulae

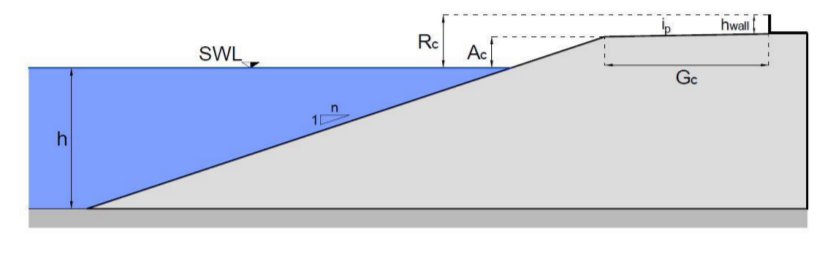


Figure 2 – Geometrical parameters

NUMERICAL MODEL IH2VOF

2DV RANS EQUATIONS

$$\frac{\partial u_i}{\partial x_i} = 0$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + g_i + \frac{1}{\rho} \frac{\partial \bar{\tau}_{ij}}{\partial x_j} - \frac{\partial (u'_i u'_j)}{\partial x_j}$$

k-ε MODEL

$$\frac{\partial k}{\partial t} + u_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} \left(\nu_t \left(\frac{\partial k}{\partial x_j} + v \right) \right) - (u'_i u'_j) \frac{\partial u_i}{\partial x_j} - \epsilon$$

$$\frac{\partial \epsilon}{\partial t} + u_j \frac{\partial \epsilon}{\partial x_j} = \frac{\partial}{\partial x_j} \left(\nu_t \left(\frac{\partial \epsilon}{\partial x_j} + v \right) \right) + C_{1\epsilon} \frac{\epsilon}{k} \nu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} - C_{2\epsilon} \frac{\epsilon^2}{k}$$

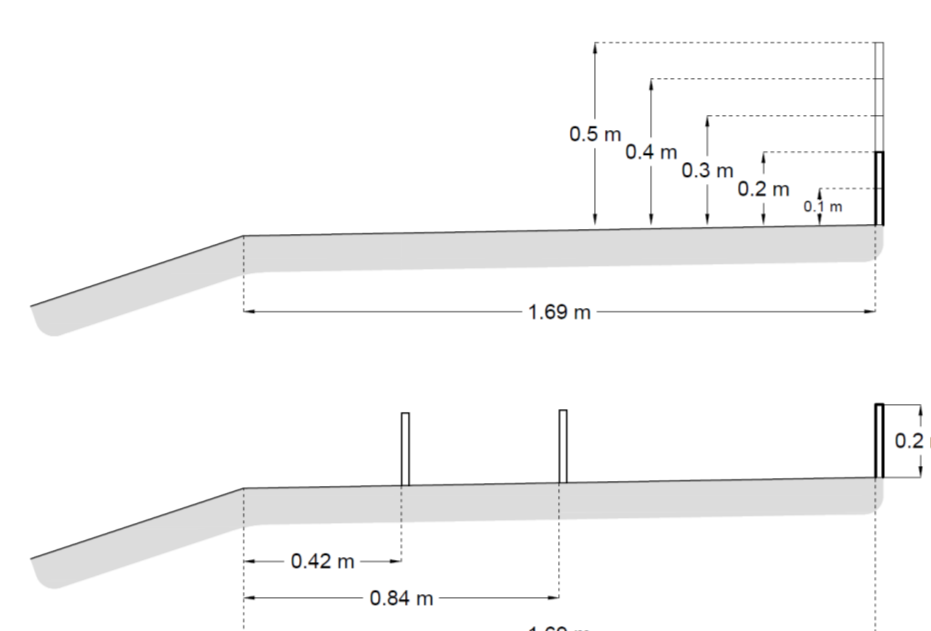


Figure 4 – Structural layouts used for the numerical simulations



The numerical wave flume reproduces the CIEM. The 2D domain is 18 m long and 2.4 m high and the max mesh resolution zone ($\Delta x=2.2$ cm and $\Delta z=1.0$ cm) is placed along the promenade and at the wall. The same analysis procedures of laboratory experiments were followed.

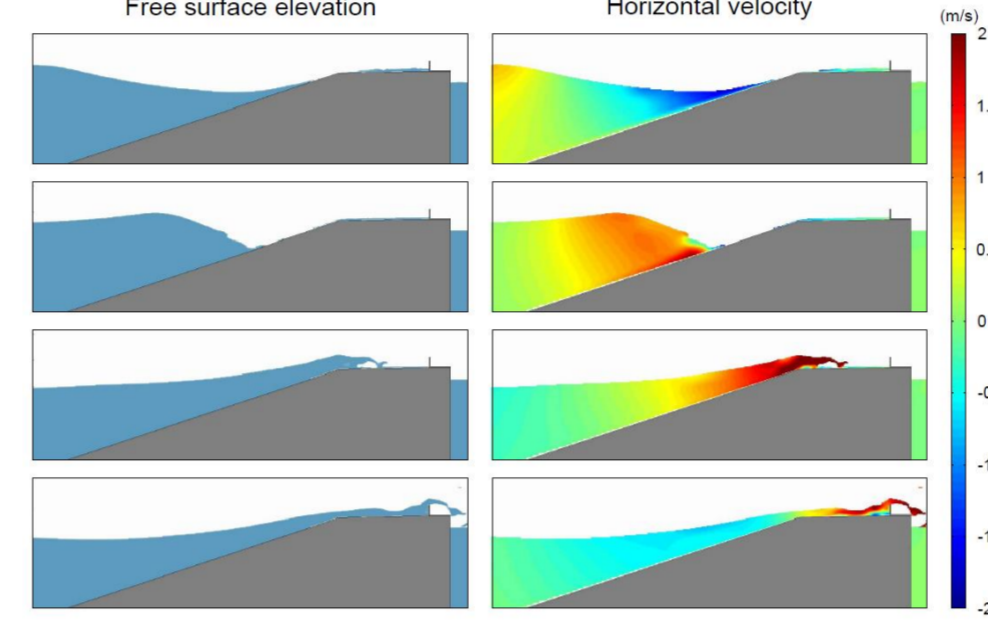


Figure 5 – Example of a hydrodynamic field provided by IH2VOF

RESULTS

- The numerical model was validated;
- New explanatory variables and different adimensionalizations for the forces were investigated;
- The best fitting line was proposed as a new prediction formula for impact forces on a storm wall (De Finis et al. (2020)).

$$F_{1/250} / (\rho g G_c R_c) = a e^{-b \left(\frac{R_c}{H_{m0} \xi_{m-1.0}} \right)^c} \left(\frac{G_c}{H_{wall}} \right)^d$$

a	b	c	d
0.947	1.407	0.753	0.468

MODEL VALIDATION

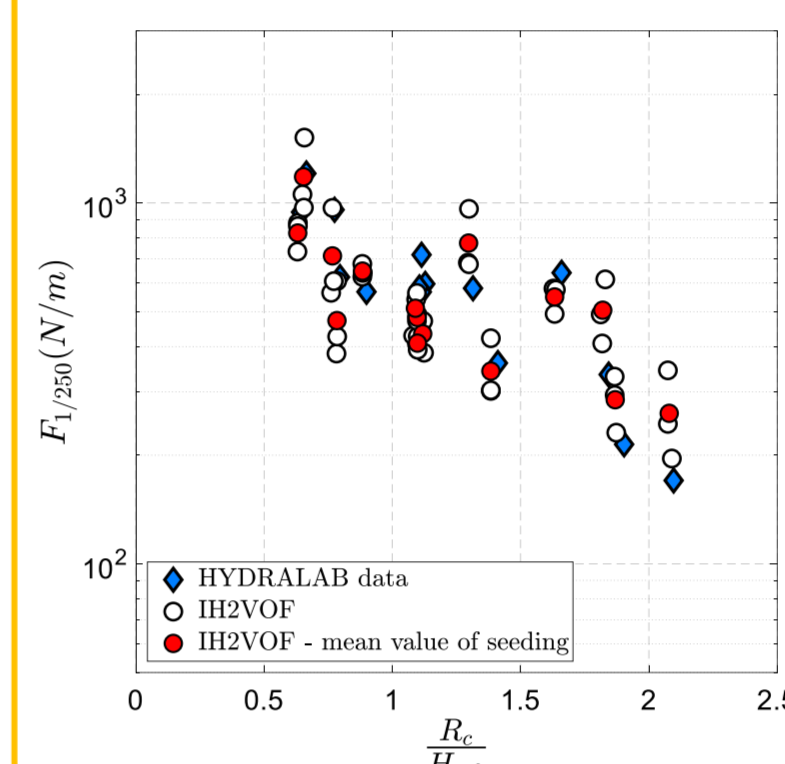


Figure 6 – Comparison between Hydralab and numerical results

NEW PREDICTION FORMULA

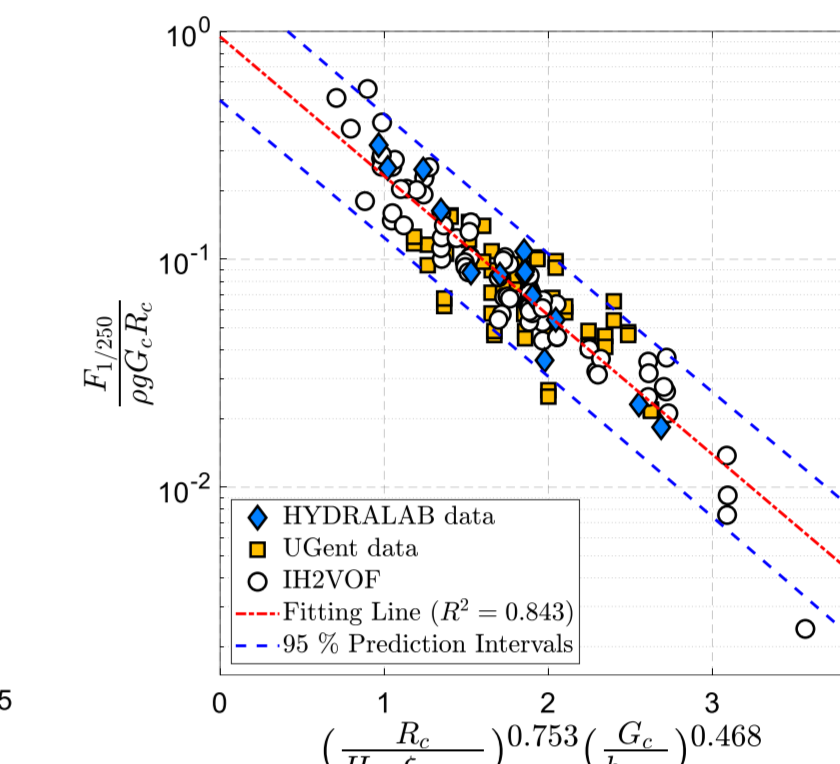


Figure 7 – New prediction formula determined from the whole dataset

IMPACTS DUE TO FILLING FLOW

INTRODUCTION

The filling flow is a hydraulic process that may occur when a water wave impinges into a confined space on a cliff or a coastal structure. If the solid surfaces are reasonably smooth, a stream of water flows in, hits the edge, fills the available space and gets shot back out along the upper surface (Peregrine & Kalliadasis (1995) and Peregrine & Thais (1996)). By solving Bernoulli's equation, for given H , h and V_1 , the magnitudes of this process can be easily determined:

$$k = \sqrt{\frac{h}{H}}$$

$$U = \frac{1}{2} V_1 \left(\frac{2k-1}{1-k} \right)$$

$$V_2 = \frac{V_1 k}{1-k}$$

$$d = H(1-k)^2$$

$$P = \frac{V_1^2 k}{2(1-k)}$$

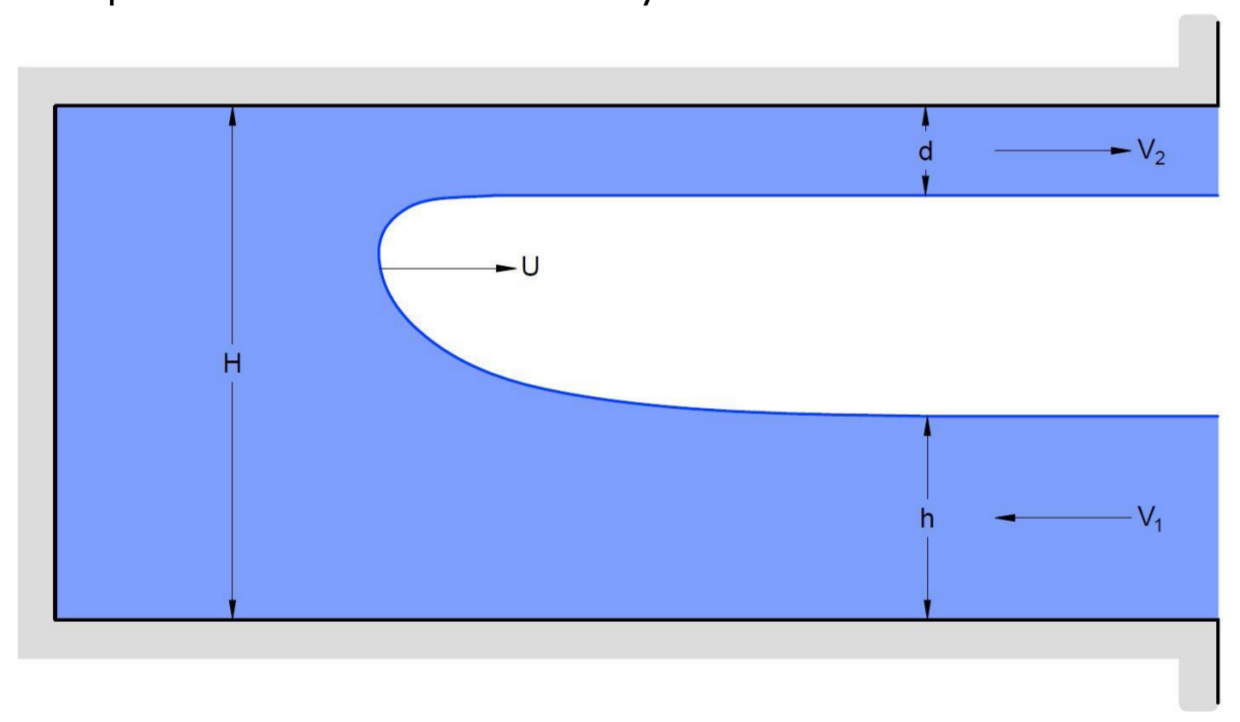


Figure 9 – Configuration of the filling flow

NUMERICAL SIMULATIONS

Before starting the experimental campaign, some numerical simulations were carried out by means of REEF3D numerical model (which solves RANS equations and uses level set method to track the free surface elevation). This analysis aimed at evaluating the input magnitudes (H , h and V_1) and the design geometrical parameters, in order to build the experimental sloshing tank.

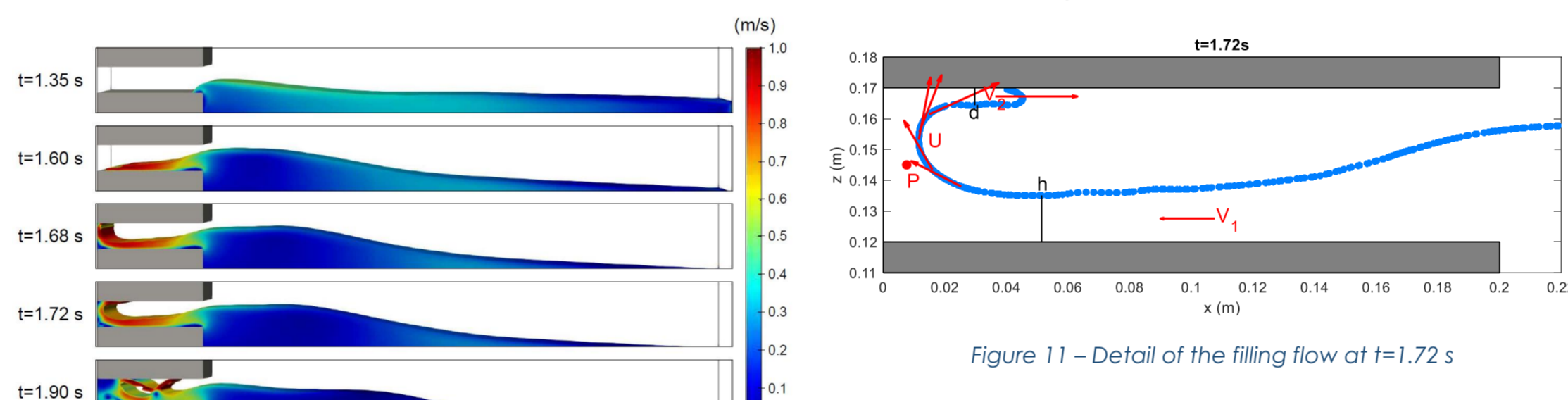


Figure 10 – Hydrodynamic field at different time instants

h (m)	V ₁ (m/s)	k	d (m)	V ₂ (m/s)	P (N/m ²)
0.0151	-0.587	0.549	0.0056	0.887	372.65

Figure 11 – Detail of the filling flow at t=1.72 s

	Numerical	Analytical
d (m)	0.0056	0.0102
V ₂ (m/s)	0.887	0.715
U ₁ (m/s)	0.053	0.064
P (N/m ²)	319.71	209.90

EXPERIMENTAL SET-UP

The experiments will be conducted at the CNR-INM Sloshing Lab. The tank is 1.04 x 1.04 x 0.14 m (Figure 12) and it will be placed on the top of a mechanical sloshing system (Figure 13), which will be moving along a single direction with an angular frequency very close to the tank lowest natural one. The flow visualizations will be performed through a digital video camera (1400 x 1400 pixels spatial resolution).

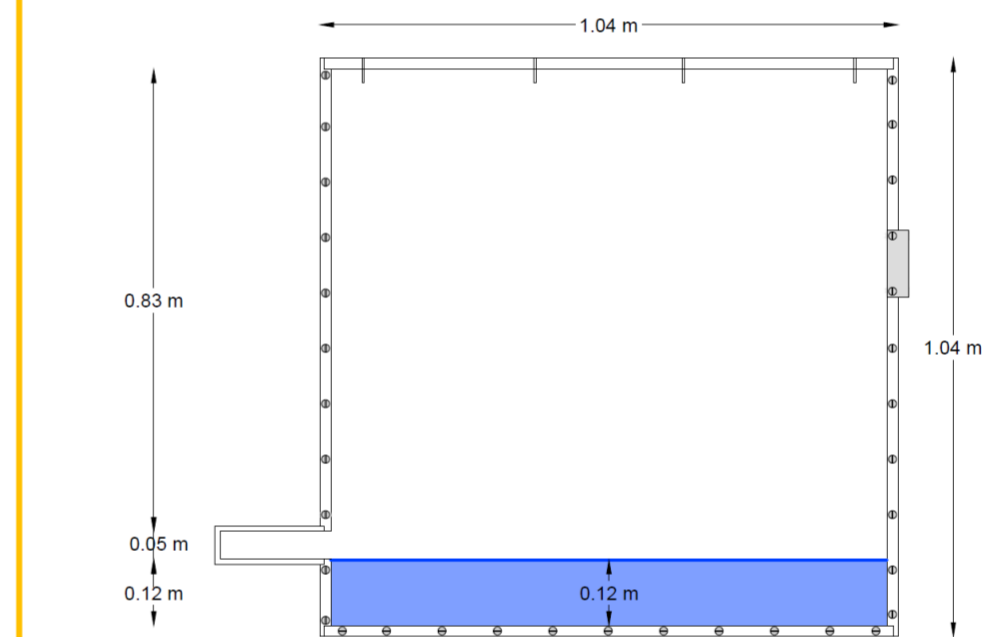


Figure 12 – Sketch of the sloshing tank



Figure 13 – Sloshing mechanism of the CNR-INM Sloshing Lab

ARPEC CAISSON BREAKWATER

EXPERIMENTAL CAMPAIGN

ARPEC (AntiReflective PERmeable Caisson) is an innovative staggered perforated caisson with hydraulic communication between seaward and landward side favouring water circulation inside the port. Physical tests were carried out at Roma Tre University wave flume (20.0 m long, 0.6 m wide and 1.0 m high), aiming at the estimation of reflection and transmission coefficients C_r and C_t . Regular and irregular waves were tested ($H=H_{m0}=1.5$ m in prototype scale).

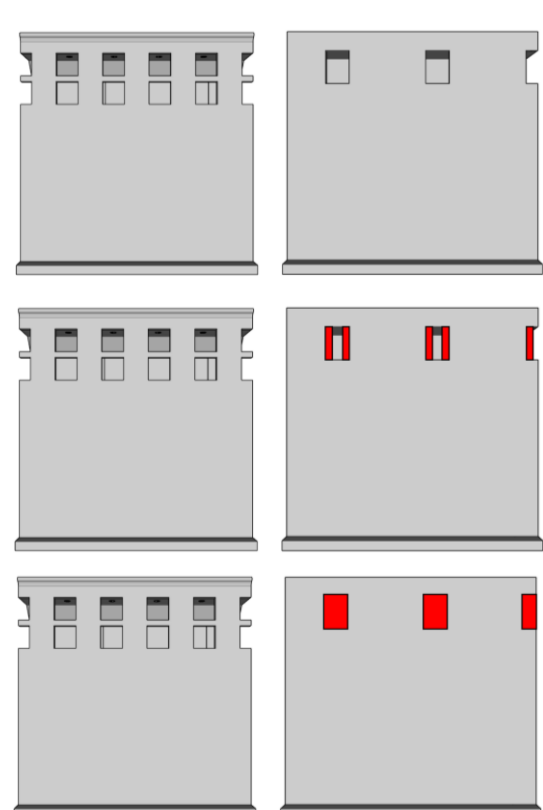


Figure 14 – Configurations tested

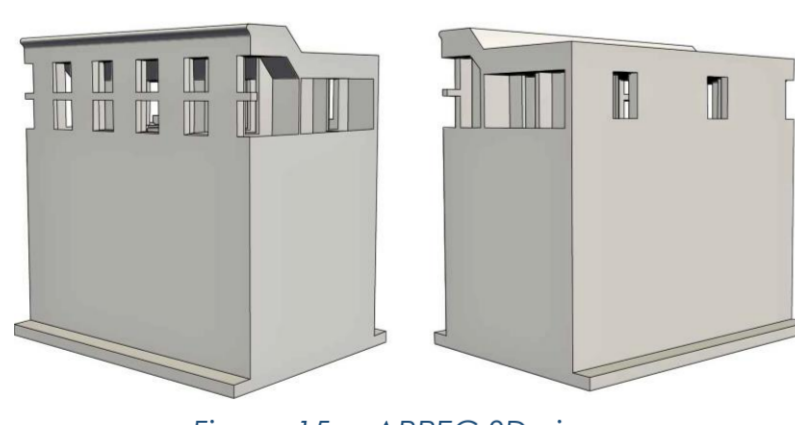


Figure 15 – ARPEC 3D view

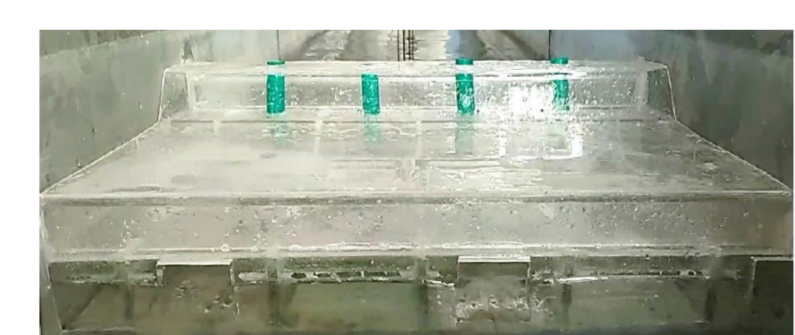


Figure 16 – ARPEC model inside the flume

NUMERICAL MODEL IHFOAM

3D RANS EQUATIONS

$$\frac{\partial u_i}{\partial x_i} = 0$$

$$\frac{\partial \rho u_i}{\partial t} + \rho u_j \frac{\partial u_i}{\partial x_j} - \frac{\partial}{\partial x_j} \left(\mu_{eff} \frac{\partial u_i}{\partial x_j} \right) = \frac{\partial p^*}{\partial x_i} - g_i \frac{\partial \rho}{\partial x_j}$$

TURBULENCE MODELS

- k-ε
- RNG k-ε
- Realizable k-ε
- k-ω
- k-ω SST

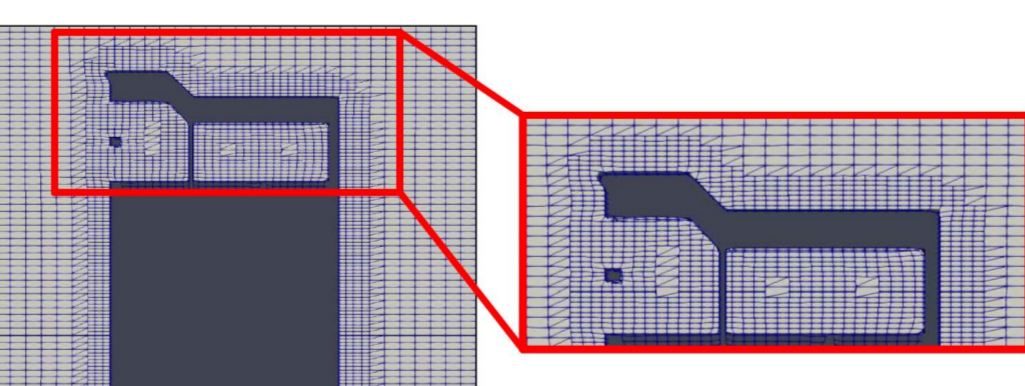


Figure 17 – Mesh grid refinement

IHFOAM IHcantabria OpenFOAM

The Roma Tre wave flume was numerically reproduced and the 3D computational domain is 8.0 m long, 0.6 m wide and 1.0 m high. A quite refined mesh grid is used ($\Delta x=\Delta y=2.5$ cm and $\Delta z=1.4$ cm). The same analysis procedures of laboratory experiments were followed. No turbulence was set.

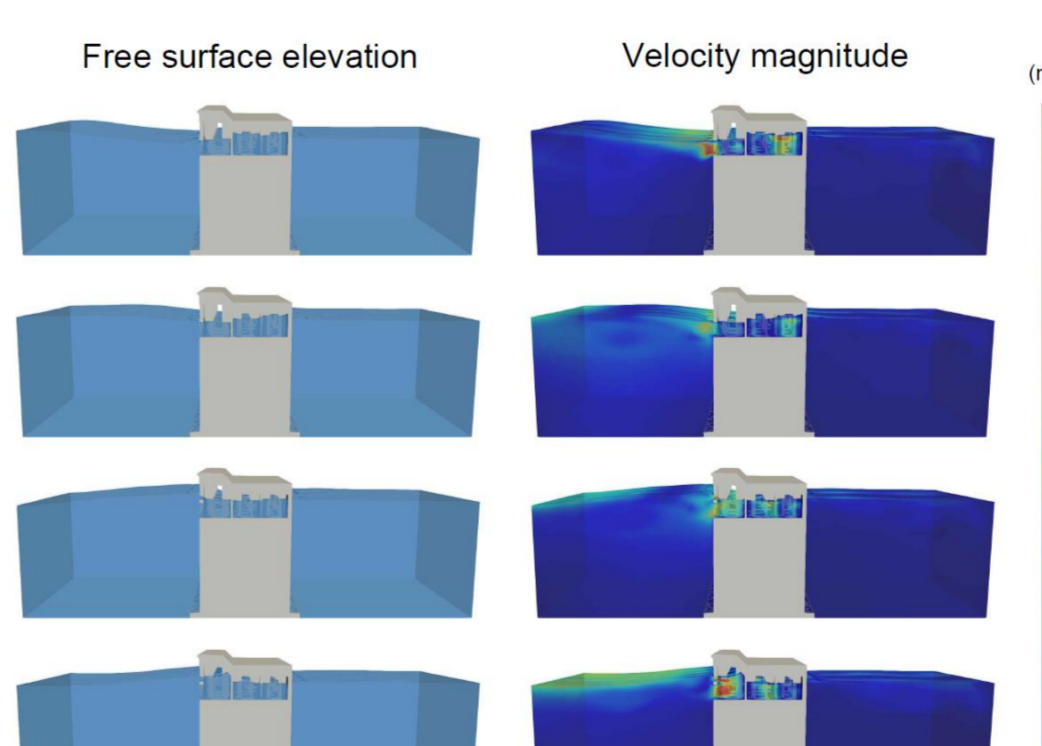


Figure 18 – Example of the hydrodynamic field provided by IHFOAM

RESULTS

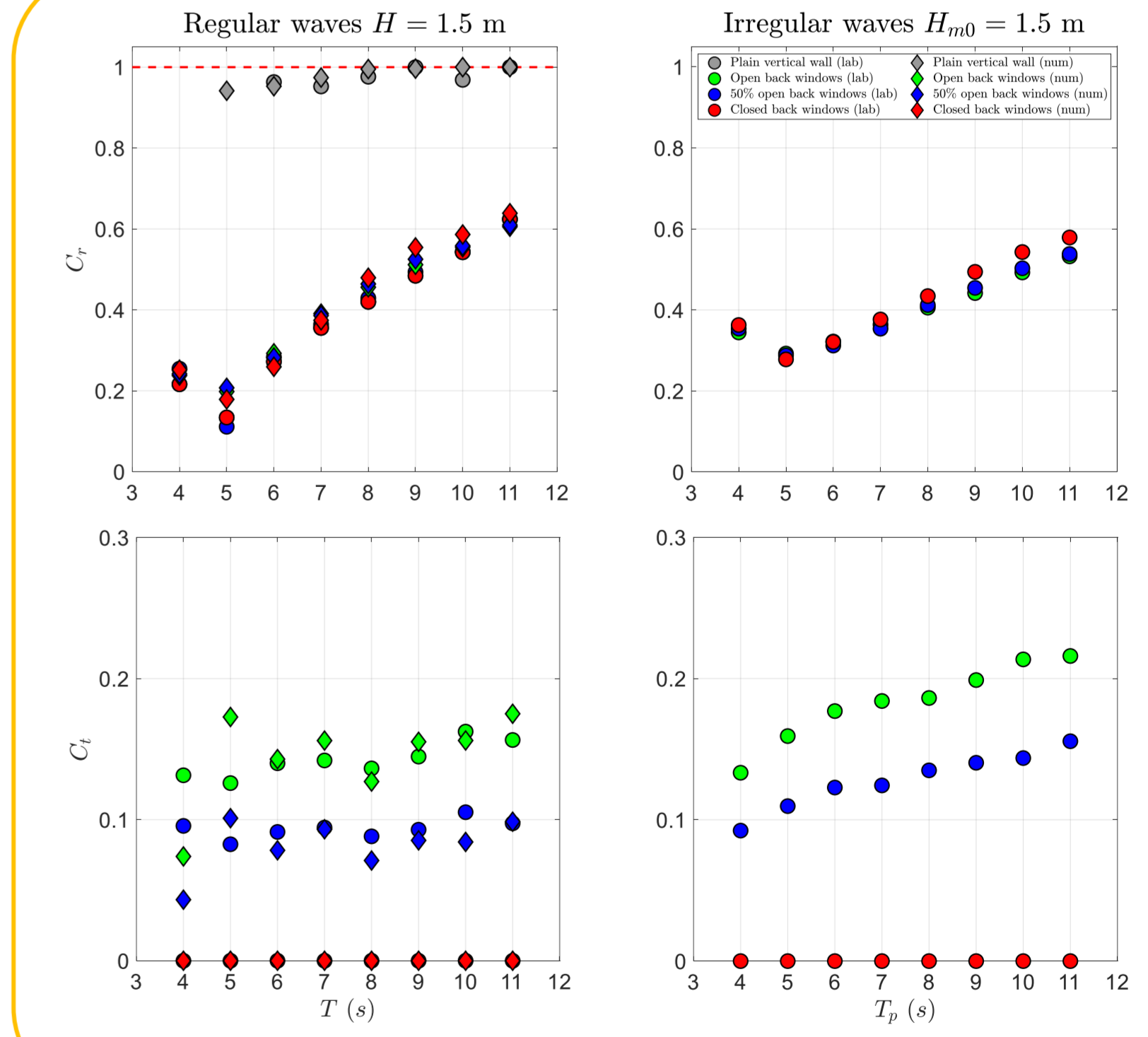


Figure 19 – Results of reflection coefficient (upper panels) and transmission coefficient (lower panels)

REFERENCES

- Peregrine, D. H., Kalliadasis, S., 1995 – Filling flows, cliff erosion and cleaning flows. *Journal of Fluid Mechanics* 310, pp. 365-374.
- Peregrine, D. H., Thais, L., 1996 – The effect of entrained air in violent water wave impacts. *Journal of Fluid Mechanics* 325, pp. 377-397.
- Van Doorslaer, K., Romano, A., De Rouck, J., Kortenhaus, A., 2017 – Impacts on a storm wall caused by non-breaking waves overtopping a smooth dike slope. *Coastal Engineering* 120, pp. 93-111.

ATTENDED COURSES

- Machine Learning** (2018) – Prof. Andrew Ng (Stanford University, online course on Coursera)
- Metodi Numerici e Statistici per l'Ingegneria Civile** (2018) – Prof. Giorgio Bellotti (Università degli Studi Roma Tre)
- Introduction to Geostatistical Analysis, with Applications using Mathematica** (2019) – Prof. Aldo Fiori (Università degli Studi Roma Tre)
- Metodi Numerici per l'Ingegneria Costiera** (2019) – Prof. Giorgio Bellotti (Università degli Studi Roma Tre)
- Scientific, Grant Writing and Presentation Skills** (2019) – Università degli Studi Roma Tre
- IHFOAM Course** (2019) – IHcantabria Institute

PUBLICATIONS

- Bellotti, G., Romano, A., De Finis, S., 2018 – Application of the IH2VOF model to evaluate forces on (flood)walls by wave overtopping. VII Congreso Nacional de la ATPYC, 4th Mediterranean Days (17-19 October 2018).
- De Finis, S., Romano, A., Bellotti, G., 2020 – Numerical and laboratory analysis of post-overtopping wave impacts on a storm wall for a dike promenade structure. *Coastal Engineering*.
- Sammarco, P., Franco, L., Bellotti, G., Cecioni, C., De Finis, S., 2020 – ARPEC: a novel staggered perforated caisson for wave absorption. *vicCE* 2020.
- Franco, L., Pepi, Y., De Finis, S., Iorio, V., Bellotti, G., Cecioni, C., 2020 – Roughness factor for multi-layer armour as overtopping estimator. *vicCE* 2020.