Chapter 63
Hydrodynamics of an Innovative Discontinuous Double Breakwater, Mixed Modeling: 2D Flume Physics and 3D Digital Modelling

Christian Raffourt, Charlie Vergnet, Vasileios Afentoulis, and Philippe Bardey

Abstract An improved design method of shore parallel discontinuous submerged breakwaters with optimal geometry is presented. In particular, the effect of breakwater openings on hydrodynamic conditions around the structures is experimentally and numerically investigated. The challenge of this study is not only validating the experimental findings using numerical methods but also investigating further alternative forms and geometries which cannot be reproduced in the wave flume. This research concerns a submerged coastal structure made out of two shore-parallel rouble mound breakwaters with openings (channels) whose main objective is to limit wave-induced set-up by pumping out and generating transverse seaward flows. Our wave flume (Fig. 63.1), extended 31 m in cross-shore and 1.8 m in along-shore direction, is equipped with a piston type wavemaker and the sea-bed is represented by a 1/36 scale distorted movable bed model. The main experimental results concern the hydrodynamic conditions in the channels, where offshore-oriented currents are presented. The numerical modeling is performed using OpenFOAM software. After the validation of experimental findings, a second task consists in expanding the structure in along-shore direction. The main objective is to assess the bias committed by the wave flume configuration. Thus, the simulations are realized with identical bathymetry, but for models four and eight times wider than the original one and with either a finite or an infinite structure. The results show that the local three-dimensional flow always exists and is negligibly influenced by reflexions on the wave flume walls.

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The initial physical model can therefore be considered as the representation of an infinite structure.

63.1   Introduction

Our goal is to define the optimal form of the shore parallel-discontinuous submerged breakwaters concerning the geometry, volume and materials of these structures. These submerged structures are often associated with wave-induced set-up while the potential energy of the flow increases in the protected area. Therefore, strong return currents are generated in the edge of the structures causing an intense sediment movement. This sandbar migration has an adverse impact on the stability of the littoral environment, affecting the performance of these structures. In order to reduce the concentrated potential area in the protected zone, an alternative shape of the breakwater system is proposed with opening (channels) so that potential energy can be converted into kinetic energy. This work concerns the assessing of hydrodynamic conditions in the vicinity of the structures, while a dedicated study is underway to evaluate the morphodynamic processes in the coastal area.

For the evaluation of hydrodynamic conditions physical experiments are carried out in a wave flume extended 30 m and 1.8 m in crosshore and alongshore direction respectively (Fig. 63.1). This wave flume (canal) is equipped with a piston type wavemaker and the sea-bed is represented by a 1/36 scale distorted movable bed model. The experimental set-up concerns structures which are characterized by an alongshore non-uniformity. It can be assumed that the initial non-uniformity cannot be fully represented by the scale model but an analogous configuration which includes 1.5 opening on the seaward rouble mound breakwater and 1 opening on the shoreward is used. The experimental procedure is based on Froude similarity low. Numerical Simulations are realized using OpenFOAM software, in order to validate the experimental findings and investigate further the coastal processes around the structures without the constraints of the experiment (side boundary effects, total space dimensions). The numerical model is based on the Reynolds-Averaged Navier-Stokes (RANS) equations. Overall a good agreement between numerical and experimental findings

Fig. 63.1 Example of the proposed structure
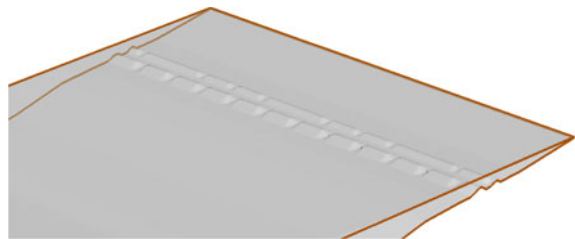
is achieved, while both approaches show that intense offshore-oriented currents are generated in the seaward side of the breakwater system around the openings. In this work, physical and numerical models collaborate intimately to increase the reliability of our investigations.

63.2 Methodology and Means

63.2.1 Method

The method used for this study is based on a hybrid approach of small scale numerical and physical models. Due to the limitations of the wave flume experiments, it is necessary to consider the following factors: (A) The narrow distance between the lateral boundary- walls of the wave flumes which restrain the flow and affect the tridimensional characteristics of the fluid motion. (B) The small scale model makes difficult the application of several similarity laws.

The physical model is therefore supported by a numerical model in order to represent the physical tests. The comparison between the physical and numerical results leads to better calibrate the numerical model. The numerical simulations are carried out on a 1:1 scale while the scale of the experiment is 1:36 complying with Froude similarity but without considering the viscous dissipation. Thus, the level of uncertainty, concerning the experimental scale, can be estimated by comparing the findings of the two methods. Similarly, the impact of the side boundaries of the physical model can also be evaluated. The physical model is the basis for a coherent approach to validating the numerical model. The numerical model makes it possible to assess the biases in experimental parameterizations. In this way, a Feedback connection of two models is achieved.

Table 63.1 Characteristics of structures

	Shoreward breakwater	Seaward breakwater
Level of crest	−0.34 m	−0.34 m
Crest width	4.0 m	4.0
Bed slope	3/2	3/2
Seaward slope of structures	3/2	2/1
Length of openings	12 m	15 m
Slope in the openings	3/2	3/2
Distance between breakwater	24 m	
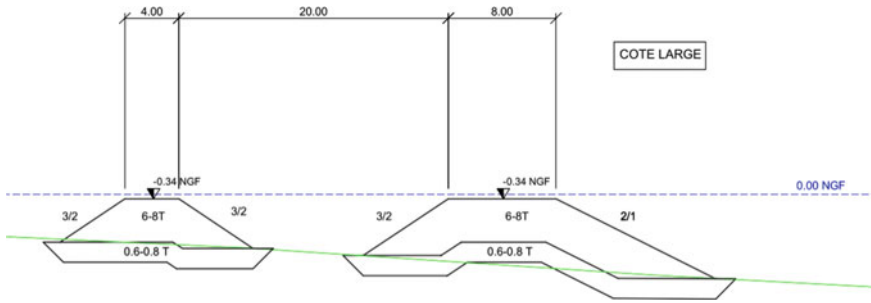
Fig. 63.2 Profile of double breakwater system in wave flume

Table 63.2 Wave climates

Parameter	Value
Still water level	+0.16 m
Wave type	Monochromatic
Wave height	3.5 m
Period	11 s

63.2.2 Configuration of Structures, Wave Conditions and Sea Bottom Characteristics

The general geometric configuration of the structure is shown in Fig. 63.1. The geometric parameters of the configuration are listed in Table 63.1. Figure 63.2 is a side profile of the structure. Moreover, the movable bottom is characterized by 23% seaward slope, 6% slope on the structures and 13% slope on the shoreface. The wave characteristics used as initial conditions are shown in Table 63.2.

63.2.3 Physical Modelling
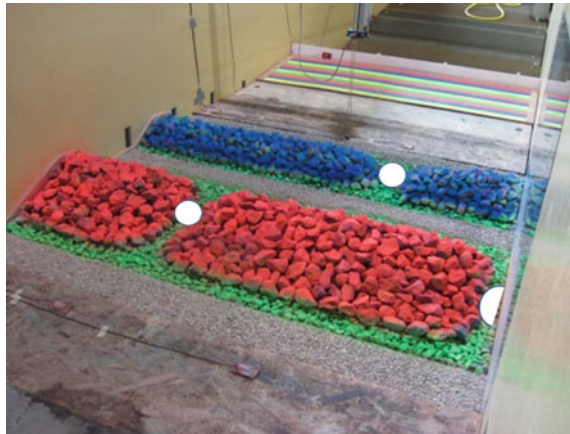
63.2.3.1 Configuration of the Model

The experiments are carried out in the 2D wave flume of ACRI IN in Sophia Antipolis. The canal is equipped with a movable bottom composed of adjustable elements with varying height and inclination, reproducing a two-dimensional bathymetry in the zone of the structures (Figs. 63.3 and 63.4). The piston-type wavemaker generates regular and irregular surface waves based on different spectral approaches including JONSWAP spectrum.

The spatial scale is 1:36. At this scale, the width of the section represented in the channel is 64.80 m and the different categories of armour layers have been defined according to the Hudson similarity law. These categories are mentioned in Fig. 63.2.

Fig. 63.3 Section of the wave flume. The piston-type wavemaker at left. The gauges are represented in fuchsia color, the two rectangles of blue color represent the two windows of the canal, the model is visible at the level of the right window, the sloping beach on the far right is not utilized, the gray vertical lines represent the fixing rails of the adjustable elements, the concrete structure of the wave channel is illustrated by the broad gray lines

Fig. 63.4 Configuration of the model. With blue the shoreward breakwater, with red the seaward breakwater. The white circles are positioned on the openings. The half-round is positioned on the additional half-opening of the breakwater


A geometrical configuration which includes 1.5 opening on the seaward rouble mound breakwater and 1 opening on the shoreward is applied in order to represent the distribution of the openings of each breakwater.

63.2.3.2   Instruments

The equipment of the experiment consists of four gauges, four pressure sensors and two reels. Their location is shown in Fig. 63.5. Three gauges (S3, S4 and S5) dedicated to the control of the incident wave characteristics are located out of the bathymetry (Fig. 63.3). The fourth gauge (S6) is placed between the structure and the beach. Two pressure sensors (CP9 and CP10) are located on the shoreward side of the structure and two others (CP5 and CP8) on the seaward side. CP9 and CP5 are positioned in front of the breakwater openings while CP8 and CP10 are positioned in front of a solid section. The two reels are placed in each of the entire openings of the two breakwaters.

The acquisition frequency is set to 200 Hz, which corresponds to a frequency of 33 Hz in real field conditions.
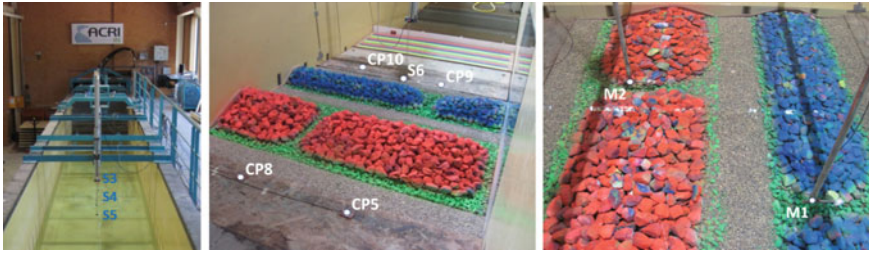
Fig. 63.5 Location of instruments in wave channel. Left: Three gauges controlling the characteristics of the incident wave (S3, S4 and S5), in the center: 4 pressure sensors (CP5, CP8, CP9 and CP10) and a sensor (S6), on the right: two reels (M1 and M2)

In addition to the instrumentation listed above, the constant slope range is used as a measuring instrument. Layers of different colors are painted in order to define the maximum runup and rundown on the video recordings.

63.2.3.3   Wave Generation

The experiments are validated when the significant height H_{m0} of the incident wave at a specific offshore location is $\pm 5\%$ of the target value defined in Table 63.2.

The duration of each experiment is 35 s which corresponds to a real duration of 210 s. This is equal to the time that an individual wave needs to reach the structure plus the time that the reflected wave needs to arrive in the wavemaker.

63.2.4   Numerical Modeling

The OpenFOAM software is applied for the purposes of this study. OpenFOAM is a free, open source CFD software released and developed by OpenCFD Ltd. OpenFOAM has an extensive range of features to solve anything from complex fluid flows involving chemical reactions, turbulence and heat transfer, to acoustics, solid mechanics and electromagnetics.

An incompressible two-phase flow solver interFoam is used to solve the Reynolds-Averaged Navier-Stokes (RANS) equations with the SST k-ω turbulence model. The PISO algorithm is utilized for the pressure-velocity coupling. The air-water interface is captured via Volume of Fluid (VOF) technique [1].

The dimensions of the model and the applied boundary conditions are described in Fig. 63.6. The numerical model is constructed on a 1:1 scale.

The incident wave is a stationary based on the linear (Airy's) theory, whose characteristics are given in Table 63.2.

Right and left sides : smooth wall law

Wave generator

Bottom : smooth wall law
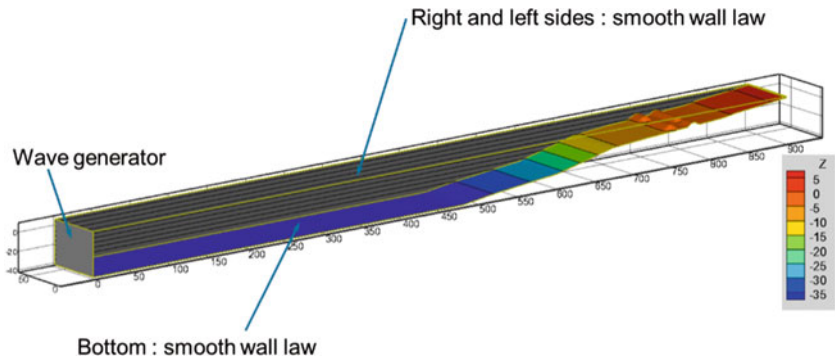
Fig. 63.6 Type of boundary conditions

At time $t = 0$, the velocity is uniformly zero. The liquid fraction α in each element is calculated so as to satisfy the criterion if $z > z_0$ then $\alpha = 0$, otherwise $\alpha = 1$.

The mesh consists of prisms with triangular bases. The horizontal dimension of the elements is approximately 1 m near the structures and widens progressively without exceeding 20 m. In vertical direction, the elements are distributed in 50 layers (Fig. 63.7).

Each numerical simulation is realized for a total duration of 210 s.

Sonde 5
Sonde 4
Sonde 3

• Capteurs de pression
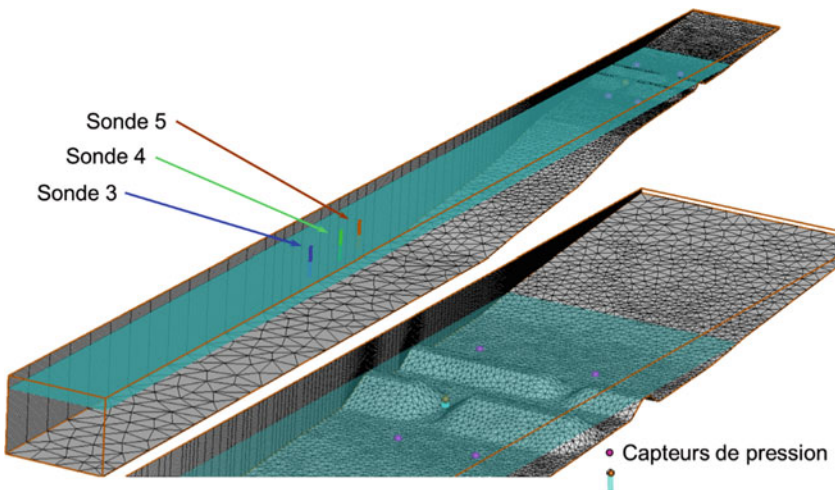
Fig. 63.7 Mesh and probes locations
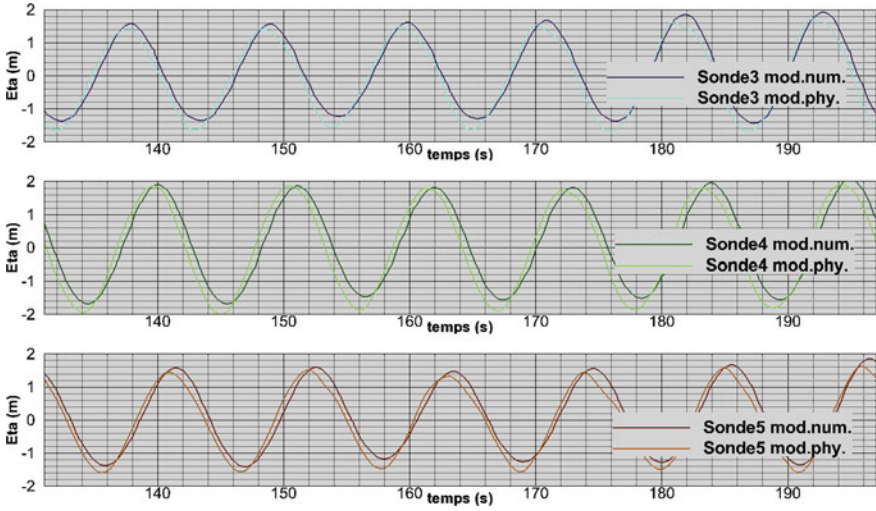
Fig. 63.8 Comparison of free surface elevation for numerical and physical models for S3, S4 and S5
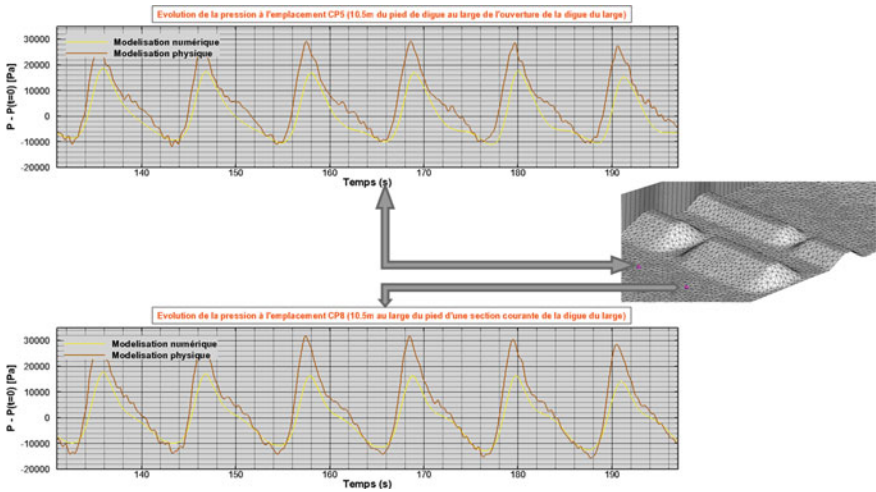

Fig. 63.9 Comparison of pressure for numerical and physical models for CP5 and CP8

63.3 Results

63.3.1 Experiment vs Numerical Model

Figures 63.8, 63.9, 63.10, 63.11 and 63.12 show the comparison of results between physical and numerical model. It is noted that a very good agreement of wave elevation record is achieved (Fig. 63.8). The pressures are well represented also by the
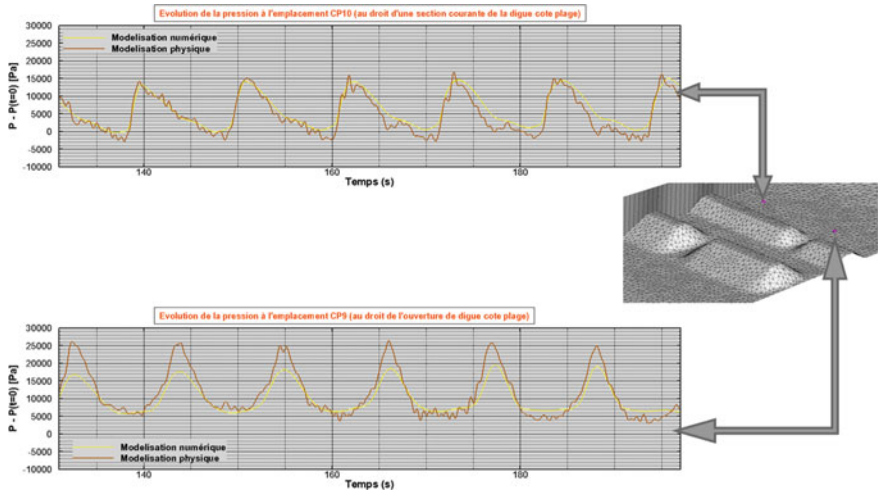

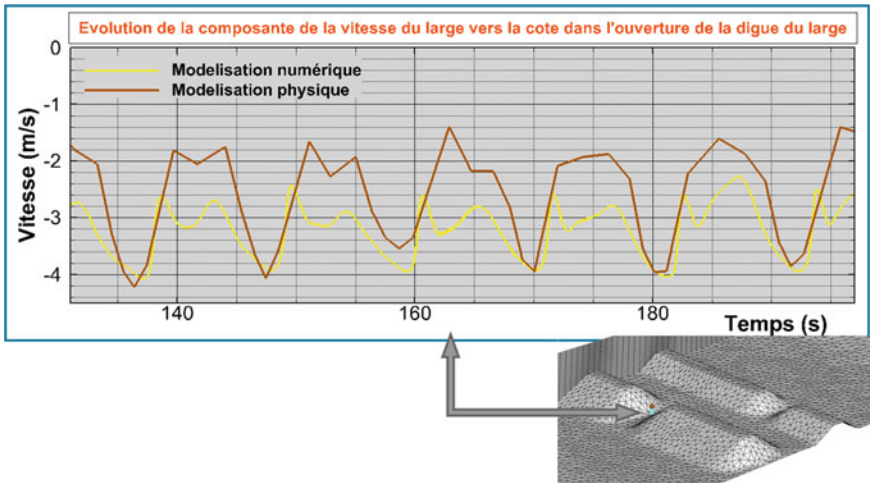**Fig. 63.10** Comparison of pressure for numerical and physical models for CP9 and CP10

Fig. 63.11 Comparison of longitudinal component of speed for numerical and physical models for M1 (negative is oriented land to offshore)
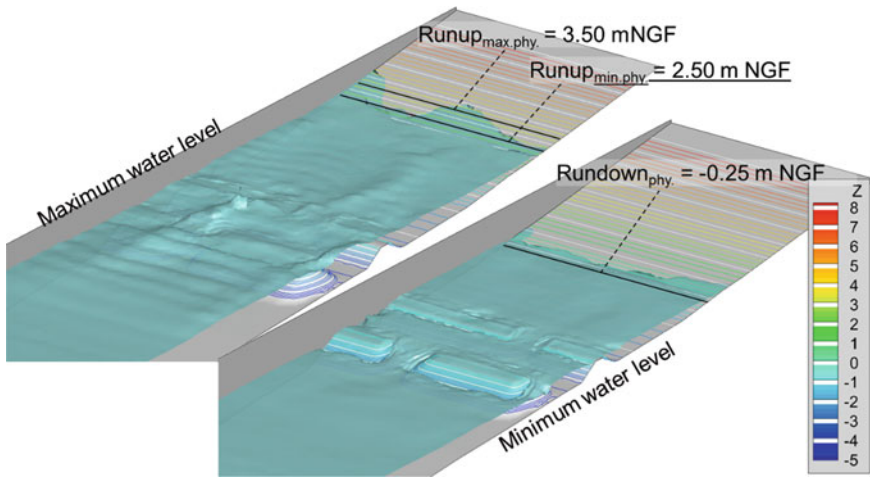
Fig. 63.12 Comparison runup and rundown for numerical and physical models for M1
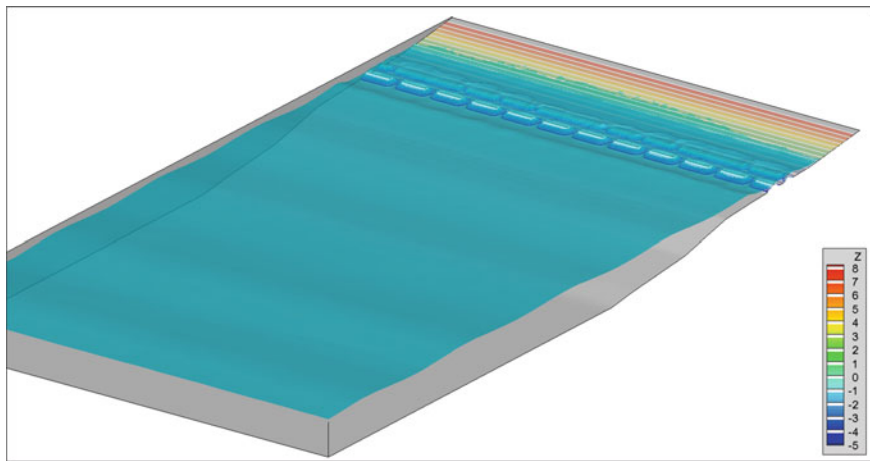

Fig. 63.13 Wide numerical model

numerical model, while the velocities in the opening of the breakwater are quite different than that of the experiment (Fig. 63.11). It should be underlined that the level of uncertainty of reels measurements is especially high. Concerning the runup and rundown (Fig. 63.12), there is a good agreement between physical and numerical model. For this last point, the two types of modelling present a three-dimensional turbulent flow in the zone between the structure and the beach.

63.3.2   Harnessing Model Capabilities

The calibration of the numerical model is not fully accomplished, but some achievements could be presented. The geometrical configuration which corresponds to a 500 m wide channel is realized with the same crosshore characteristics as that of the experiment and with a coarse vertical discretization (Fig. 63.13). In Fig. 63.14, the velocities in one of the openings shows that in this configuration offshore-oriented currents are obtained as in the case of the initial set-up.

Another scenario corresponds to a breakwater system with openings at the edges. The graphs in Fig. 63.15 show the cross-sectional component of velocity in the offshore breakwater openings. There is still a strong offshore-oriented current. In this
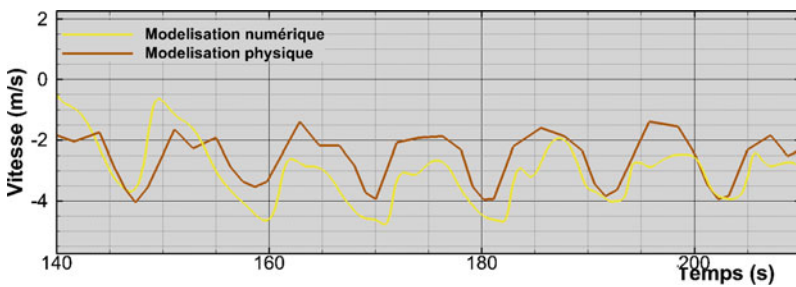

Fig. 63.14 Velocities measured in a single point around the opening of the seaward breakwater of the wide model
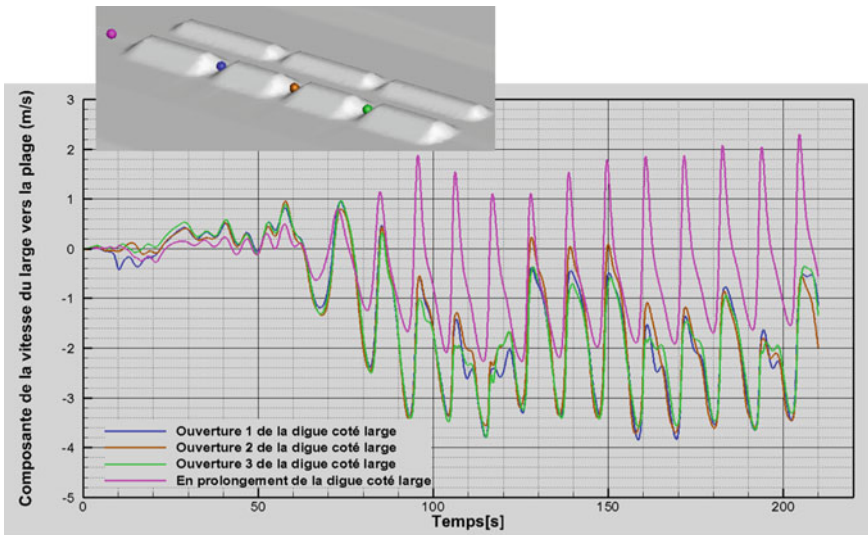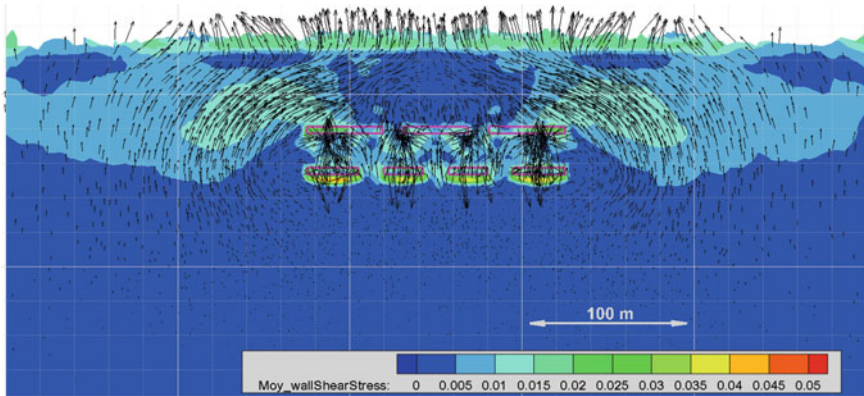

Fig. 63.15 Longitudinal component of the velocities in the openings of the seaward breakwater for the case of a breakwater system with openings at the edges

Fig. 63.16 Bottom shear stresses for the case of a breakwater system with openings at the edges

configuration of relatively narrow structure, we see in Fig. 63.16 that the opening of the system at the edges causes the generation of significant longshore currents, which can affect the stability of the coast.

63.4 Conclusions

This study concerns a double shore parallel breakwater system, whose performance is investigated using a hybrid numerical and physical modelling. The physical model is carried out in a 1:36 scale wave channel. The numerical simulations are realized using of the solver interFoam of OpenFOAM free software.

The still uncompleted study enlightens very encouraging results for both numerical model validation aspects as well as for the use of the wave flume concerning this type of discontinuous works.

There is still important work to (i) improve numerical modeling for different wave conditions modeled in physical channel (ii) complete the harnessing of the numerical model in expanded channel configurations.

This hybrid modeling could be followed by a further study in wave flume in order to learn more about optimal configurations.

Reference

1. Hirt CW, Nichols BD (1981) Volume of fluid (VOF) method for the dynamics of free boundaries. J Comput Phys 39:201–225