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The Effects of Submerged Berms on the Seabed Pressure around Rubble Mound Breakwaters

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Abstract: Berms deployed at the toe of conventional breakwaters may be needed to reduce bottom settlements and to limit scour in front of the structure. Due to their influence upon the wave loads acting on the armor, the submerged berms may be also effective in increasing the stability of the armor layer, as well as of the soil-foundation system, if compared to straight sloped conventional breakwaters. This research deals with the influence of submerged berms on the wave-induced dynamic pressure in front of and beneath rubble mound breakwaters, whose detection is paramount for the evaluation of momentary liquefaction phenomenon. The present paper summarizes the preliminary results, obtained from experimental tests and numerical models.

Keywords: Rubble mound breakwaters, submerged berms, wave action, experimental modelling, numerical modelling

1 Introduction

The design of rubble mound breakwaters is aimed to ensure structural response, by taking into account the actions of both waves and currents (e.g. Lamberti et al., 2005; Di Risio et al., 2010; De Girolamo et al., 2017; Saponieri et al., 2018), also related to storm surge events (e.g. Pasquali et al., 2015, 2019). Past research studies (e.g. Celli et al., 2018) showed that modifying the conventional rubble mound configuration by introducing a submerged berm, can increase the hydraulic stability of the structure. Nevertheless, the stability of breakwaters could be threatened also by geotechnical causes, such as liquefaction. This phenomenon is related to the wave-induced pressure acting on the seabed. Besides increasing the armor layer stability, Celli et al. (2019) showed that deploying a submerged berm is effective also in reducing wave-induced momentary liquefaction, compared with a straight sloped conventional rubble mound breakwater. The numerical evaluation of seabed pressure, coupling condition for the soil model (e.g. Li et al., 2018), was carried out by means of SWASH (Zijlema et al., 2011), a phase resolving numerical model. The lack of experimental data in terms of seabed pressure makes needed the validation of the numerical results that, in turn, can be used within the frame of a comparative study. Then, with the aim to validate numerical models in terms of seabed pressure, a quantitative comparison with experimental data is required. In the past, research studies were carried out indeed. However, they focused on the pore pressure distribution inside rubble mound breakwaters (i.e. in the filter layer and the core), whose importance is well recognized within slope stability analysis and filter layer design (de Groot et al., 1994).

In particular, Oumeraci and Partenscky (1990) presented experimental results from large scale tests, in terms of spatial distribution of wave-induced pore pressure within rubble mound breakwaters. Based on the works of Biesel (1950) and Le Mèhautè (1958), the authors concluded that the height of pore pressure oscillation of a propagating pressure wave, decreases exponentially with the distance to the breakwater interface, according to a linear damping model.

Troch (2001), analyzed prototype and large-scale data (from Oumeraci and Partenscky, 1990), presenting a practical calculation method for the attenuation of the pore pressure heights in the breakwater core. The same conclusion on the pore pressure distribution was found by using a validated numerical model.

Unlike the previous authors, Cantelmo et al., (2010) studied the spatial distribution of seabed pressure under a rubble mound breakwater, comparing the experimental results with the numerical ones, obtained by using a one-dimensional numerical model.

By following the strategy adopted by Cantelmo et al., (2010), the main aim of the research proposed herein is to provide an experimental dataset in terms of seabed pressure around and beneath rubble mound breakwaters with submerged berms, useful for validating numerical models. Moreover, the experimental and numerical results can be helpful to evaluate the role of submerged berms in attenuating the seabed pressure beneath porous structures, whose importance is well recognized within the soil stability instead.

The experimental tests have been carried out at the Environmental and Maritime Hydraulic Laboratory (LIam) of the University of L'Aquila. Time histories of water levels and seabed pressures have been collected to be used as a database for validation purposes.

The water waves hydrodynamic properties have been calculated by means of two different numerical models, i.e. SWASH (e.g. Zijlema et al., 2011) and IH-FOAM (e.g. Higuera et al., 2014a). The comparison among the numerical results will allow to establish which one is more suitable in detecting the seabed pressure under porous structures. SWASH is an open-source phase resolving numerical model, solving the non-linear shallow water (hereinafter referred to as NLSW) equations with a non-hydrostatic pressure term, a simplified form of the Navier-Stokes equations. It has been widely validated and used within several research studies, including the wave-structure interaction (e.g. van den Bos et al., 2014; van den Bos et al., 2015; Celli et al., 2018). IH-FOAM is a solver developed within the OpenFOAM® computational library and solves the Volume Averaged Reynolds Averaged Navier-Stokes (hereinafter referred to as VARANS) equations. It should yield more accurate flow simulation results, at the expense of high computational costs if compared to those required by SWASH numerical model. Even IH-FOAM has been largely used for simulating coastal hydrodynamic processes, including wave-structure interaction (e.g. Higuera et al., 2014b; Castellino et al., 2018).

The present paper illustrates the results of one of the forty-two experimental tests. The experimental results have been compared to the computed ones, obtained by using SWASH numerical model. The OpenFOAM® simulations are still in progress and just a qualitative comparison between numerical results is shown in Section 5.

2 Experimental investigation

Experimental tests have been performed in a wave flume (45 m long, 2 m high and 1.5 m wide) at the Environmental and Maritime Hydraulic Laboratory of the University of L'Aquila. The wave flume is equipped with a piston type wave generator that can be used to generate regular and irregular waves characterized by target spectra. The wave generator system is equipped with an Active Reflection Compensation System based on the real-time reflection analysis proposed by Frigaard and Brorsen (1995).

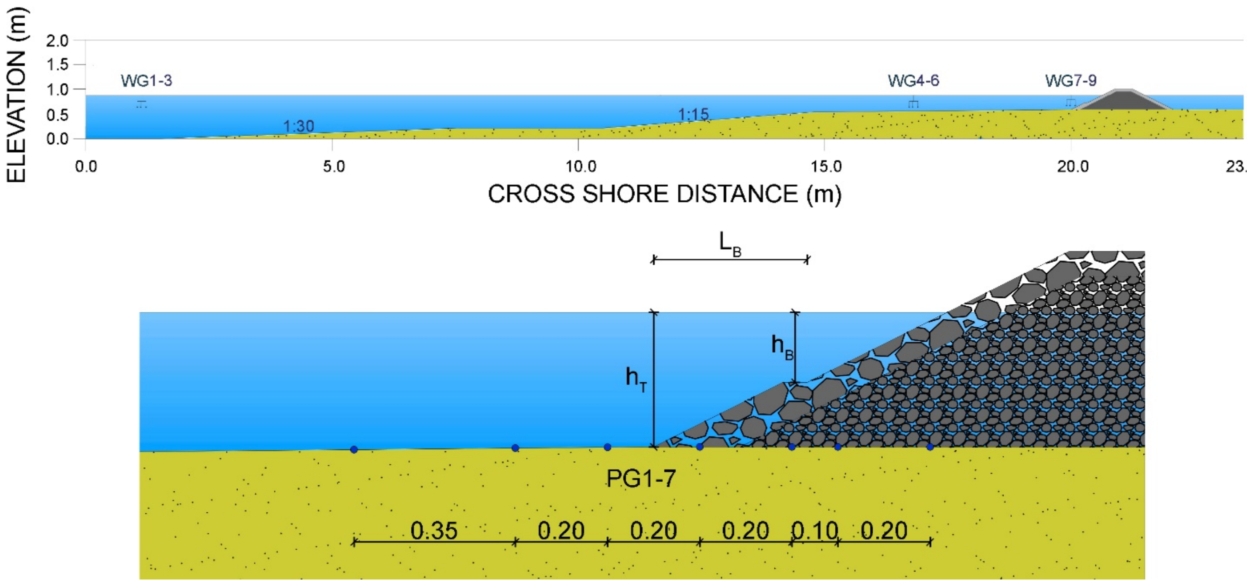

Fig. 1. Upper panel: sketch of the experimental layout. Wave gauges deployed along the flume are referred to with the symbol "WGs". Lower panel: zoom on the structure. Pressure gauges deployed on the seabed are referred to with the symbol "PGs" (dimensions are in meters).

Fig. 2. Layout of pressure gauges deployed in the wave flume.

The physical model reproduces a conventional rubble mound breakwater with a submerged berm. Concerning the sketch of Fig. 1, the tested configuration is characterized by a berm length L_B = 0.33m, a water depth over the berm h_B = 0.15m and a water depth at the toe of the berm h_T = 0.29m. The armor elements are characterized by a mean diameter (D_{n50}) equal to 50mm. The free surface elevations time series have been collected through a series of nine wave gauges (hereinafter referred to as WGs) deployed along the wave flume. The gauges have been arranged in groups of three in order to apply standard reflection analyses (e.g. Goda and Suzuki, 1977; Mansard and Funke, 1980).
During the experimental test, almost 1000 irregular waves, obtained synthetizing Jonswap target spectrum (H_s = 0.08m, T_p = 1.3s, γ= 3.3) have been reproduced. The time series of dynamic pressure have been collected by means of seven pressure gauges (hereinafter referred to as PGs) placed in a trench formed in the bottom of the flume (see Fig.1 and Fig.2). The experimental results in terms of water levels have been used to validate SWASH numerical model. Then, the observed seabed pressures have been compared to the computed ones.

3 Numerical investigation

3.1 SWASH numerical model

It is an open source phase resolving numerical model for simulating non-hydrostatic, free surface, rotational flows (Zijlema et al., 2011). The model solves the shallow water equations including a non-hydrostatic pressure term that can be derived from the incompressible Navier-Stokes equations and a module for porous flow based on Forchheimer's formulations. In the research described herein, the numerical model has been employed by using two terrain-following layers in the vertical direction in the one-dimensional case. The layer-integrated continuity equation for the layer $1 \leq k \leq K$ (K=2) reads as follows (Zijlema and Stelling, 2005):

$$\frac{\partial h_k u_k}{\partial x} - u\frac{\partial z}{\partial x}\Big|_{zk-\frac{1}{2}}^{zk+\frac{1}{2}} + w_{k+\frac{1}{2}} - w_{k-\frac{1}{2}} = 0 \qquad (1)$$

where x is the horizontal coordinate, h_k is the thickness of the layer k, z is the elevation of the interface between two layers, u is the layer-integrated horizontal velocity, $w_{k\pm1/2}$ is the vertical velocity at the interfaces between two layer.

The layer integrated horizontal momentum equation reads as follows:

$$\frac{\partial h_k u_k}{\partial t} + \frac{\partial h_k u^2{}_k}{\partial x} + \bar{u}^z_{k+1/2}\omega_{k+1/2} - \bar{u}^z_{k-1/2}\omega_{k-1/2} + gh_k\frac{\partial \xi}{\partial x} + \frac{\partial h_k \bar{q}^z_k}{\partial x} - q_{k+\frac{1}{2}}\frac{\partial z_{k+\frac{1}{2}}}{\partial x} + q_{k-\frac{1}{2}}\frac{\partial z_{k-\frac{1}{2}}}{\partial x} = 0 \qquad (2)$$

where t is the elapsed time, $\bar{u}^z_{k\pm1/2}$is the horizontal velocity estimated at the layer interfaces $z_{k\pm1/2}$, $\omega_{k\pm1/2}$ is the vertical velocity relative to layer interfaces $z_{k\pm1/2}$, g is the gravitational acceleration, $\zeta$is the free surface elevation, $q_{k\pm1/2}$ is the non-hydrostatic pressure defined at the layer interfaces, $\bar{q}^z_k$ is the arithmetic mean of the non-hydrostatic pressure at the layer interfaces $z_{k\pm1/2}$.

The layer integrated vertical momentum equation reads as follows:

$$\frac{\partial h_{k+1/2} w_{k+1/2}}{\partial t} + \frac{\partial h_{k+1/2}\bar{u}^z_{k+1/2}}{\partial x} + \bar{w}^z_{k+1}\bar{\omega}^z_{k+1} - \bar{w}^z_k\bar{\omega}^z_k + 2\bar{q}^z_k = 0 \qquad (3)$$

where $h_{k+1/2}$ is the arithmetic mean of the layer thicknesses h_k and h_{k+1}, $\bar{w}^z_{k(+1)}$ is the arithmetic mean of the vertical velocities at the layer interfaces $z_{k(+1)\pm1/2}$, $\bar{\omega}^z_{k(+1)}$is the arithmetic mean of the vertical velocities relative to the layer interface at the layer interface $z_{k(+1)\pm1/2}$. The detail of numerical procedures can be found in Zijlema and Stelling (2005, 2008) and Smit et al., (2013).

3.2 SWASH validation

Based on a preliminary sensitivity analysis, the one-dimensional domain has been discretized by a constant horizontal spacing $\Delta x = 0.01$ m. In order to properly describe wave dispersion also in the offshore zone, a fixed number of two terrain-following layers in the vertical direction has been selected, each of them characterized by equal thickness between the bottom and the moving free surface.

The rubble mound breakwater has been simulated through a porous layer within the computational domain. A volumetric porosity values of 0.20 have been used for the berm and the armor layer respectively. The offshore boundary is considered as weakly reflective and a water level time series is imposed. It reproduces irregular waves, obtained synthetizing the incident energy spectrum, observed at WG1. The Sommerfeld radiation condition has been applied to the onshore side of the numerical domain.

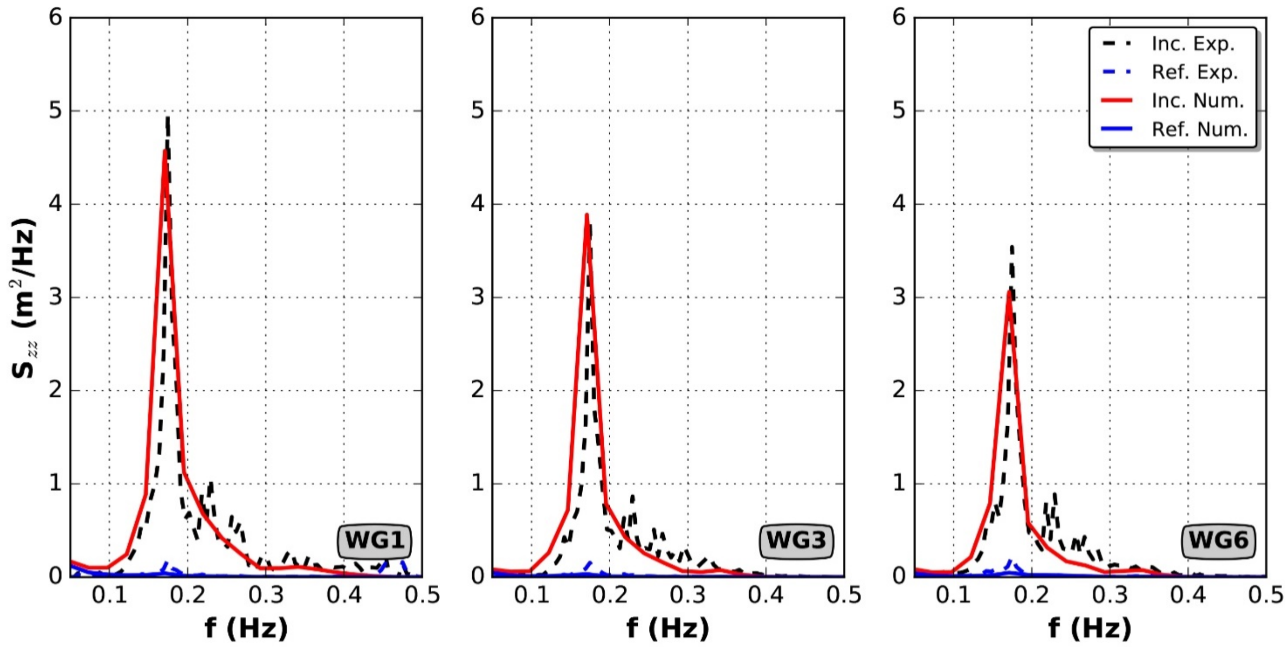

Fig. 3. Incident (higher values) and reflected (lower values) wave energy density spectra of the observed water levels (dashed lines) and of the computed water levels (continuous lines) estimated by means of the standard method proposed by Goda and Suzuki (1977); from left to right, the diagrams refer to the locations of wave gauges WG1, WG3 and WG6 (see Fig. 1).

Fig. 3 shows the energy density spectra of the incident and reflected waves estimated by means of Goda and Suzuki (1976) method. Spectral results inspection reveals that during the propagation toward the breakwater, the energy peak tends to decrease because of the bottom friction and the wave breaking.

In general, computed and observed spectra are almost similar. For the three locations, the computed incident spectra show slightly higher energy in the low-frequency band than the observed ones. On the contrary, it appears how the computed incident energy tends to be slightly lower in the high-frequency band. Apart from these deviations, the agreement between the experimental and numerical results confirms the ability of SWASH to correctly reproduce the wave propagation phenomenon and the wave-porous structure interaction as well.

4 Results and discussions

With the aim to evaluate the reliability of SWASH to catch the spatio-temporal variation of wave-induced seabed pressure, a comparison with experimental data has been carried out. In this regard, Fig. 4 shows the computed and observed 5% (upper panel) and 50% (lower panel) exceedance individual wave pressures heights.

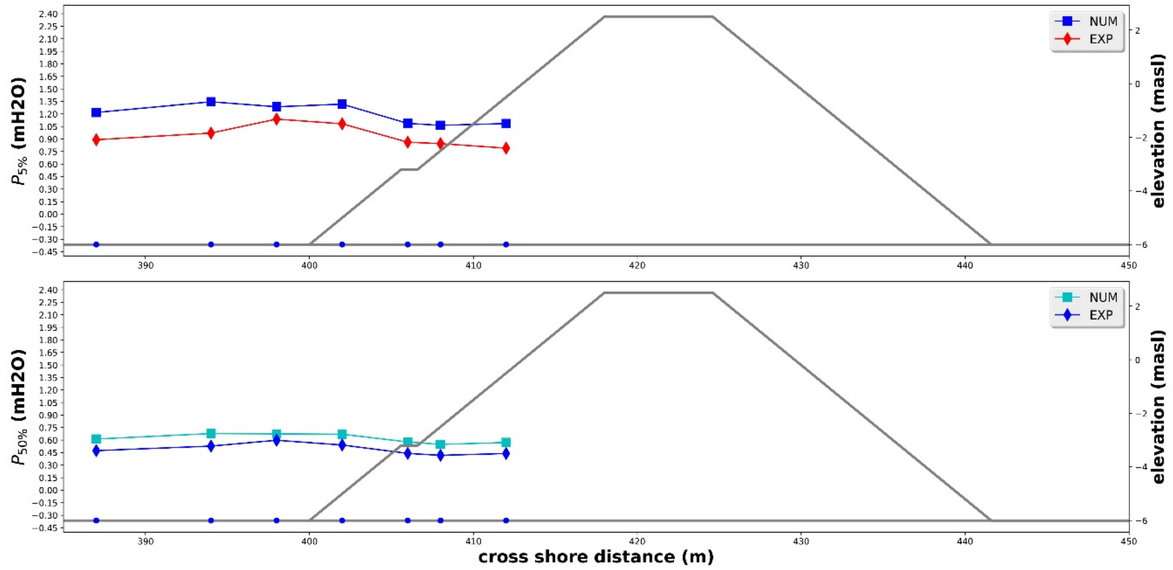

Fig. 4. Upper panel: 5% exceedance individual wave pressure heights observed (red diamonds marked line) and computed by means of SWASH (blue squares marked line). Lower panel: 50% exceedance individual wave pressure heights observed (blue diamonds marked line) and computed by means of SWASH (cyan squares marked line).

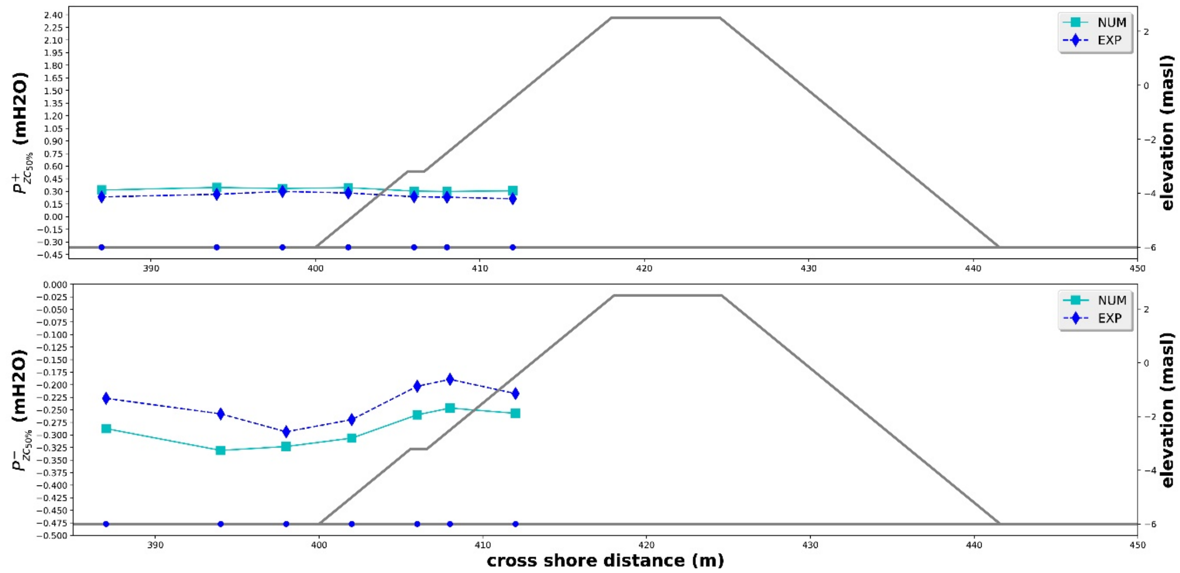

Fig. 5. Upper panel: 50% exceedance individual wave pressure crests observed (blue diamonds marked dashed line) and computed by means of SWASH (cyan squares marked line). Lower panel: 50% exceedance individual wave pressure troughs observed (blue diamonds marked dashed line) and computed by means of SWASH (cyan squares marked line).

From the inspection of the upper panel, it appears how higher the computed pressure heights are. In particular, the difference between the results tends to decrease up to PG3, and then slightly increasing, up to remain constant under the porous structure.

Even considering the gap between the results, it should be stressed how SWASH is capable to catch the pressure heights spatial trend. It appears that the higher the value of the exceedance percentage, the lower the difference between the observed and computed results. If the 50th percentile is considered, the agreement between the wave pressure heights is satisfactory. Indeed, the gap showed in the upper panel of Fig. 4 is due to the higher values of the individual wave pressure heights. Moreover, from the inspection of Fig. 5, it appears that the differences are due to the SWASH overestimation of pressure troughs (lower panel), being the individual wave pressure crests in agreement (upper panel). It should be underlined that the momentary liquefaction occurs during the passage of wave troughs if the upward pore pressure gradient exceeds the initial vertical effective stress (e.g. Celli et al., 2019).

Consequently, an overestimation of the seabed wave pressure troughs could lead to an overestimation of the soil depths potentially prone to momentary liquefaction occurrences, which could be regarded positively if a safe rationale is employed. Once recognized the SWASH capability to simulate water-wave hydrodynamic properties, albeit with an overestimation of wave pressure troughs, the next step is focused on the evaluation of IH-FOAM in detecting the spatio-temporal evolution of the seabed pressure, within the frame of wave-porous structure interaction. Until now, the OpenFOAM® simulations are still in progress. Within the model calibration phase, a preliminary numerical setup has been designed. In particular, the 2DV domain will be discretized by adopting an orthogonal mesh characterized by a cell resolution equal to 0.02 m along x-direction and 0.05 m along z-direction (1175 x 26 elements). The porous structure will be modeled by using a porosity value n = 0.2. A still water level will be applied as initial condition. The incident energy spectrum computed at WG1 will be been applied as offshore boundary condition, where also an active absorption boundary condition will be imposed (e.g. Higuera et al., 2013).

Even though the preliminary stage of the OpenFOAM® simulations, a qualitative evaluation of the numerical results obtained from the two different models has been carried out.

In this respect, Fig. 6 shows the comparison of computed maximum ($P_{SWZC\text{-}max}$, obtained by means of SWASH and $P_{OFZC\text{-}max}$, obtained by means of IH-FOAM) and minimum ($P_{SWZC\text{-}min}$, $P_{OFZC\text{-}min}$) individual wave-dynamic pressure crests and troughs values, respectively, for a generic rubble mound breakwater, under the action of regular waves (H=4m, T =8s).

Nevertheless, under the porous structure, the values of the maximum dynamic pressure computed by SWASH are lower than those obtained by using IH-FOAM.

The SWASH overestimation of pressure troughs (see Fig. 4,5), together with the non-perfect agreement between the numerical results of Fig. 6, confirm how important could be carrying out ad-hoc OpenFOAM® simulations.

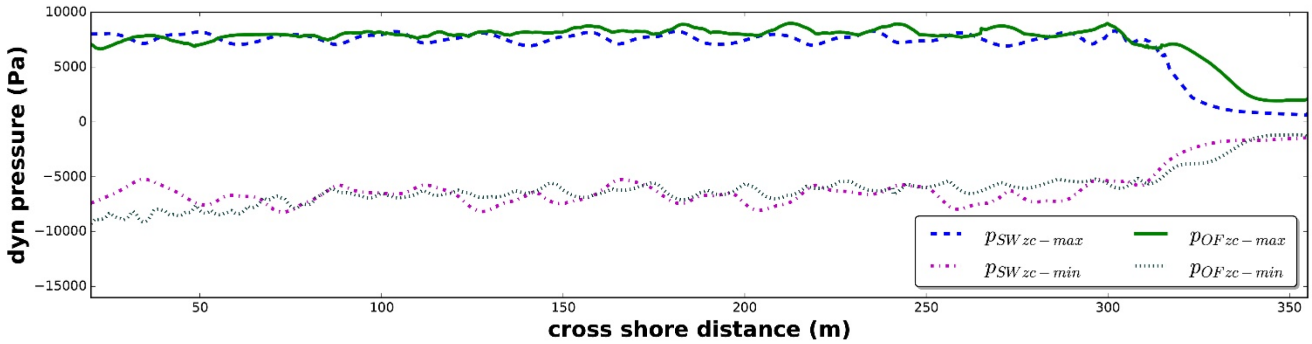

Fig. 6. Spatial distribution of the maximum and minimum wave-dynamic pressure crests and troughs computed by using SWASH (blue and magenta dashed lines) and IH-FOAM (green continuous and cyan dotted lines).

5 Concluding remarks

Experimental tests have been performed to investigate dynamic seabed pressure evolution within the wave-porous structure interaction framework.

The experimental data have been used as a database for validation purposes. In this respect, the reliability of a one-dimensional SWASH model in detecting the dynamic pressure acting on the seabed has been tested through a comparison with observed data, giving encouraging results, even if preliminary.

Nevertheless, a slightly numerical overestimation of wave troughs was found. This has motivated the idea to carry out numerical simulations by using also an OpenFOAM® solver, which can simulate two-phase flows within porous media, by solving a new set of VARANS equations instead.

The OpenFOAM® simulations are still in progress. The comparison between experimental and numerical data from the two different numerical models will allow establishing which numerical tool is suitable for detecting the wave-induced seabed pressure.

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