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OpenFoam-Based Numerical Modeling of Overland Flow in Indealized Constructed Environment: Laboratory Validation

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Abstract: This study employed the OpenFOAM framework coupled with the olaFlow solver to simulate wave-driven overland flows in an idealized coastal community, with a particular focus on the validation of the numerical model as the first preliminary research study. A series of large-scale 1:16 laboratory experiments in a three-dimensional wave basin, conducted under a wide range of water levels, wave conditions, and structural configurations, including a seawall (SW) and a submerged breakwater (SB), served as the benchmark for validation. Model performance was assessed by comparing time series of offshore and onshore free-surface elevations, horizontal velocities, and hydrodynamic loads (forces and pressures) on building arrays in an idealized constructed environment. Furthermore, the validation results exhibited a strong agreement between measured and simulated hydrodynamic and loading variables, with normalized root-mean-square errors (NRMS) less than 15.32% and an index of agreement (IA) up to 0.95. These findings establish that the olaFlow solver can reliably reproduce time series of hydrodynamic parameters, providing a robust foundation for subsequent evaluation of coastal flooding mitigation strategies.

Keywords: Laboratory, openFOAM, overland flow, coastal communities, mitigation structures.

1. INTRODUCTION

Coastal flooding driven by hurricanes, tsunamis, and storm surges poses significant risks to low-lying coastal regions, and these risks are further exacerbated by the rapid growth of coastal populations associated with economic and transport development [1, 2]. Several historical disasters, such as Hurricane Katrina (2005), illustrate the catastrophic consequences of extreme events, both in terms of human casualties and structural damage [3]. While substantial progress has been made in advancing prediction of storm surge and tsunami propagation offshore, comparatively fewer studies have addressed storm- or tsunami-driven overland flow and its interactions with nearshore communities with a series of near-coast buildings [4].

Previous studies [5, 6] have primarily focused on the hydrodynamic loads and flow features around individual structures, employing both laboratory experiments and numerical modeling. These studies have demonstrated that wave-induced forces and overturning moments increase with building submergence, and complex flow phenomena such as hydraulic jumps, vortices, and wakes emerge in the vicinity of structures. More recently, attention has shifted toward the cumulative effects of coastal building arrays, often referred to as macro-roughness elements, which can significantly reduce inundation depths, flow velocities, and hydrodynamic forces during storm surges and tsunamis [7]. Their effectiveness, however, depends strongly on building orientation, spacing, and the presence of background currents [8]. Both experimental and numerical studies have shown that staggered or multi-row configurations enhance flow shielding, reduce momentum transfer, and modify vortex dynamics, emphasizing their potential role in coastal flood mitigation strategies [1, 9]. However, coastal communities have been protected by flooding mitigation structures, which influence hydrokinematic patterns and loadings on near-coast structures, which have not been fully quantified in the previous studies [10].

Coastal protection structures, such as seawalls, are also widely used to reduce wave overtopping and mitigate the impacts of flooding on inland areas. Taller

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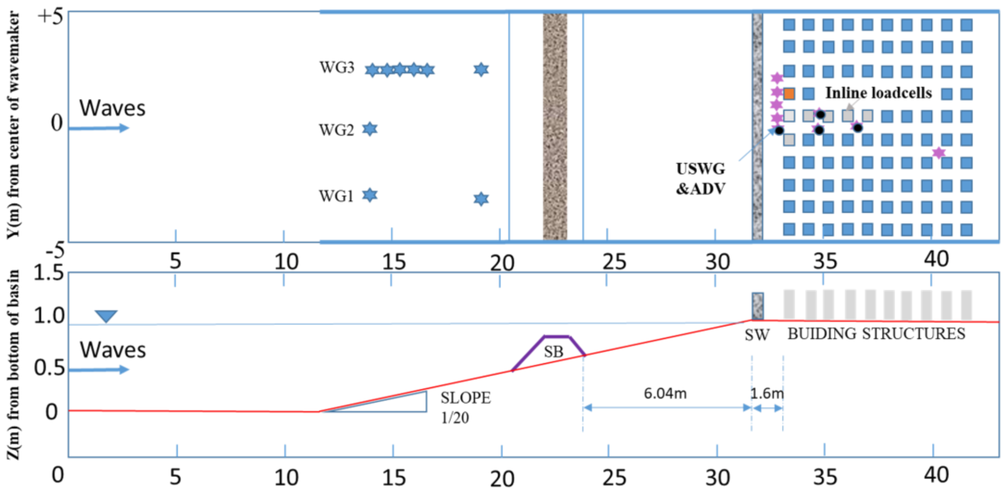

Fig. 1. Plan and cross-shore views of experiments(a-b) (dimensions are not in scale and redrawn from [10]).

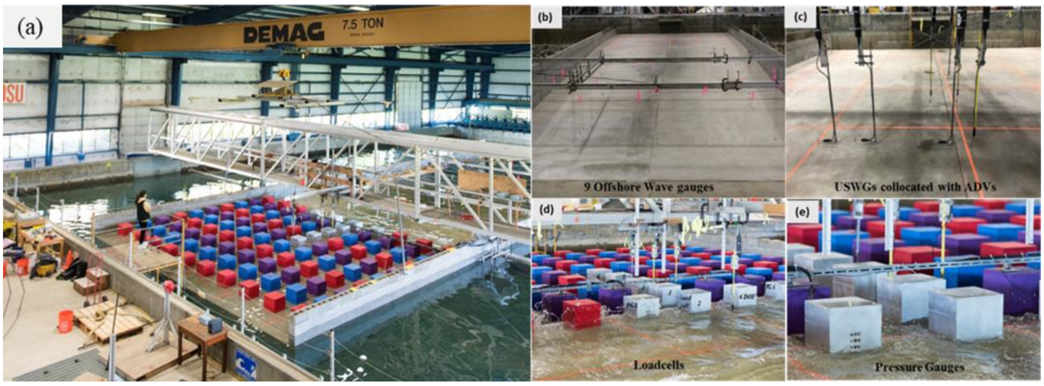

Fig.2. Snapshot (a) and instrumentations deployed in the experimental tests (b-d).

seawalls are generally more effective at limiting wave-induced forces on structures but often come with higher economic and environmental costs [11]. Thus, introducing a retrofitting structure to support the seawall in mitigating extreme wave-driven overland flow is of great importance. Alternatively, submerged breakwaters have gained attention as eco-friendly, aesthetic, and cost-effective offshore defenses [12, 13, 14]. They dissipate incoming wave energy before reaching the shoreline, thereby reducing wave loads on seawalls and adjacent coastal infrastructure. Despite these theoretical advances, the combined hydrodynamic performance of submerged breakwaters, seawalls, and urban building arrays remains insufficiently investigated.

The present study builds on recent experimental investigations by [10], which employed 1:16 scale physical models to examine offshore submerged breakwaters in conjunction with seawalls. While [15] examined the effectiveness of seawalls and submerged breakwaters in mitigating tsunami-driven overland flows using the OpenFOAM model. The current study extends these efforts with random wave-generated inland flows to comprehensively analyze detailed flow processes, including wave shoaling, breaking, runup, and the resulting forces and pressure distributions on coastal building arrays under varying surge and storm conditions. The preliminary objective of this work is to evaluate the predictive effectiveness of the numerical model in simulating overland flow propagation in complex built environments, thereby providing a robust foundation for assessing integrated coastal defense strategies.

2. LABORATORY EXPERIMENTS

The laboratory experiments were carried out in the three-dimensional wave basin at Oregon State University, using a piston-type wavemaker in a 48.8 m × 26.5 m × 2.1 m flume at a geometric scale of 1:16 (Figure 1). The bathymetry consisted of an 11.7 m flat bottom, followed by a 20 m beach with a 1:20 slope, and a 10 m elevated horizontal platform representing the coastal plain. On this platform, 100 cubic building elements (0.4 m per side) were arranged in a 10 × 10 straight array to simulate idealized urbanized coastal development. The buildings were spaced 0.4 m in the streamwise direction and 0.6 m transversely, with the first row positioned 1.6 m from the shoreline, following earlier experimental configurations [10]. Three structural configurations for flood mitigation were tested in addition to the baseline (no protection), including a trapezoidal submerged breakwater (SB: crest width of 0.676 m, height of 0.25 m, 1:1-side slopes) placed 24.45 m from the wavemaker; a

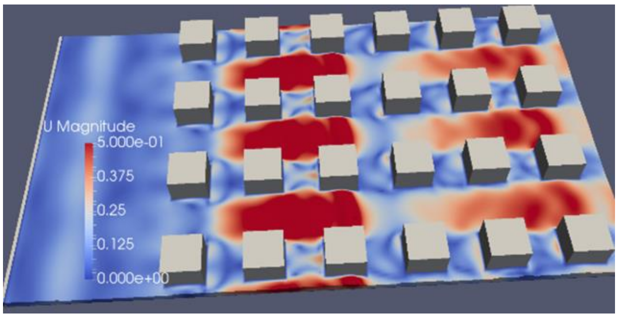

Fig. 3. A representative snapshot of overland flow interacting with the constructed environment.

low-lying full-length seawall (SW: 0.12 m × 0.036 m) located at x = 31.7 m; and a combined breakwater and seawall arrangement (SWSB).

Several advanced instrumentations utilized to measure surface elevations, velocities, forces, and pressures were illustrated in Fig. 2. Instrumentation included nine resistance wave gauges (WG1–WG9) to record offshore free surface elevations and eight ultrasonic wave gauges (USWGs) to capture inland inundation depths (Figure 2a-b). Four of the USWGs were collocated with Nortek acoustic Doppler velocimeters (ADVs) to measure three-dimensional velocities (Figure 2b). In addition, five horizontal load cells (LCs) were installed in the first five building rows to measure cross-shore forces (Figure 2c).Among the 100 building elements, eight aluminum blocks were fitted with a six-degree-of-freedom (6DOF), five load cells (LCs), and twelve pressure gauges (PGs) to monitor forces and pressures at a sampling frequency of 1000 Hz, while WGs, USWGs, and ADVs operated at 100 Hz. This study employed random wave cases with wave height ranging from 0.1 m to 0.2 m, and a peak period of 2.25 s. The surge levels were installed from 0.96 m to 1.1 m, representing dry and flooded scenarios in the constructed environment. The detailed description of the experimental setup is presented in the previous work [10].

3. NUMERICAL SIMULATION

The olaFlow solver computes fluid motion based on the continuity and incompressible Reynolds-Averaged Navier–Stokes (RANS) equations, discretized using the finite volume method (FVM) and solved with the PIMPLE algorithm, which combines the SIMPLE and PISO schemes to resolve velocity–pressure coupling [16]. Free-surface elevation is captured using the Volume of Fluid (VOF) method, where the phase fraction (α) represents the proportion of water in each cell [8]. Turbulence effects are modeled using the *k–ω SST* closure scheme, which has been shown to more effectively reproduce tsunami-like, partially separated

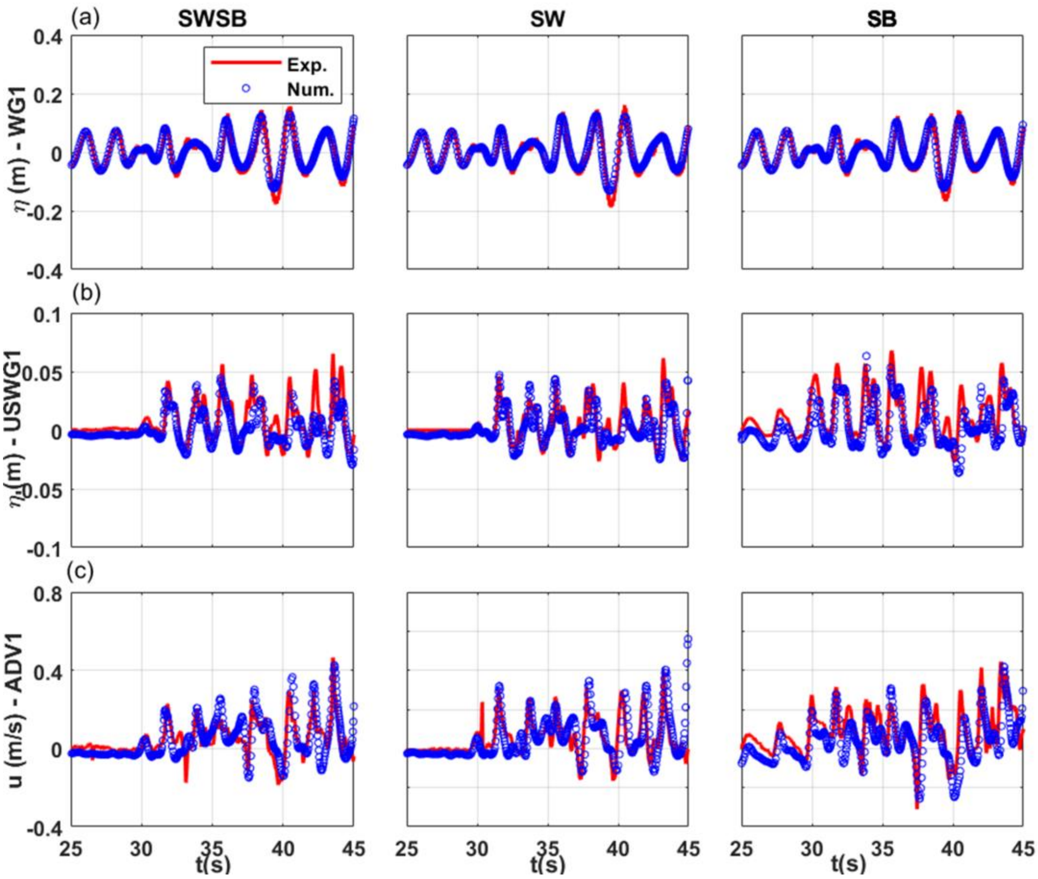

Fig. 4. Comparison of measured and simulated offshore, onshore wave heights and velocities along the flume test.

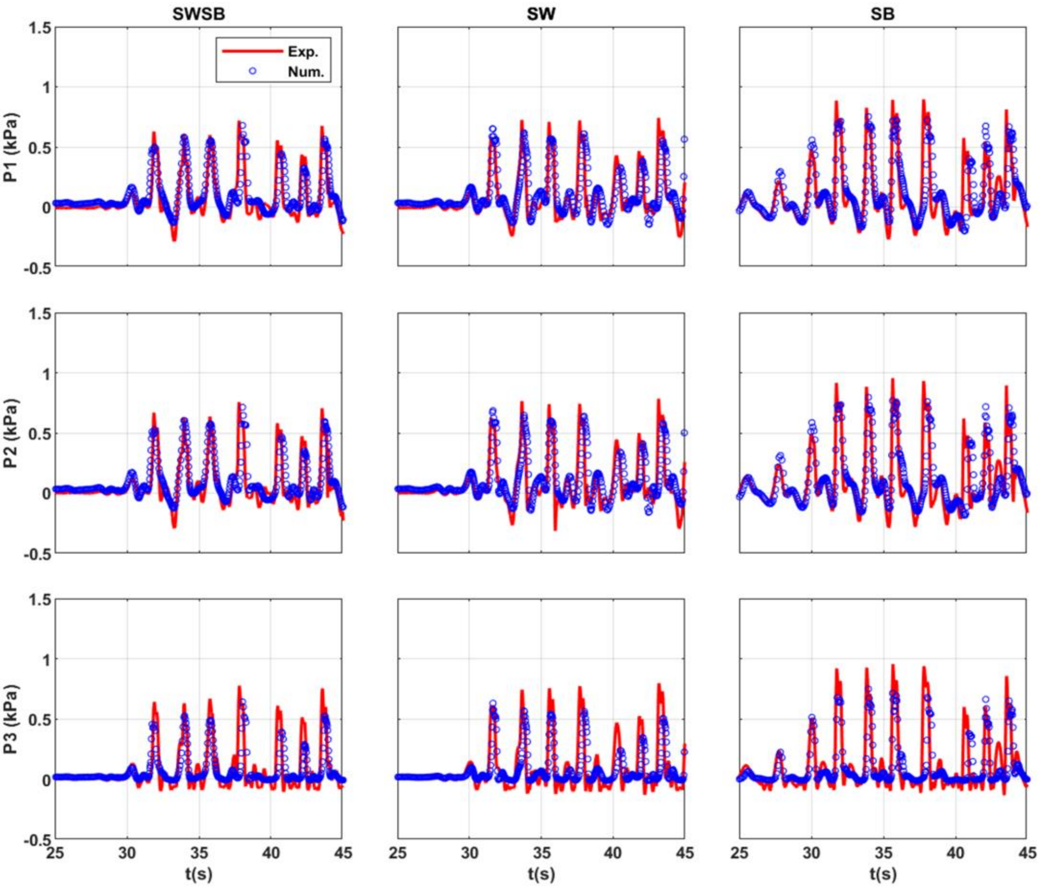

Fig. 5. Comparison of measured and simulated pressures in the first building row.

flows around building arrays than alternative turbulence models [15].

The numerical model implemented in OpenFOAM employed "wall-function" approaches to resolve near-wall turbulence, with a "no-slip" boundary condition applied to the flume bed and all structural surfaces, enabling an accurate representation of bottom friction and boundary-layer development. The lateral boundaries of the 10-m-wide computational domain were prescribed as "slip" walls, enabling the tangential velocity component to remain unconstrained and minimizing artificial lateral shear stresses. An "atmospheric" boundary condition was applied at the top boundary to permit free-surface deformation and pressure adjustment consistent with air–water interactions. The numerical wavemaker is facilitated using measured time series of wave displacement and wave height in the laboratory to generate incident waves.

Grid sensitivity tests were conducted with the finest resolutions of 0.02 m, 0.01 m, and 0.005 m in the building areas. While the coarser meshes reproduced low-water-level conditions reasonably well, only the finest grid (0.005 m) accurately captured high-water-level scenarios and sharp peaks in force and pressure, resulting in approximately 96 million total nodes. Seawall, submerged breakwater, and buildings were further refined using the "snappyHexMesh" technique, which subdivided each background cell into eight smaller cells to improve representation of flow and structure interactions. Numerical simulations were performed for 150 s using water and air density and kinematic viscosity properties of ρ_w = 1000 kg/m³, ν_w = 1×10^{-6} m²/s, and ρ_a = 1 kg/m³, ν_a = 1.48×10^{-5} m²/s, respectively. A Courant number of 0.5 was maintained with an adaptive time step to ensure stability. Each run required approximately ten days of wall-clock time using 24 processors on rack and tower servers. The numerical model was run simultaneously across multiple cores of the Dell PowerEdge R640 Server. A detailed description of the numerical model setup is illustrated in [15]. Figure 3 illustrates a representative snapshot of overland flow interacting with the building arrays.

4. RESULTS AND DISCUSSIONS

The predictive performance of the olaFlow model was assessed by comparing computed results with measurements for offshore and onshore free surface elevation (η), cross-shore velocity (u), horizontal force (F), and pressures (P) in the constructed environment.

4.1. Validations on hydrodynamic variables

A representative validation for the most serious wave case with a wave height (H) of 0.2 m and a wave period (T_p) of 2.25 s over three structural configurations is conducted. Due to the large number of instruments, comparisons were conducted at some selected

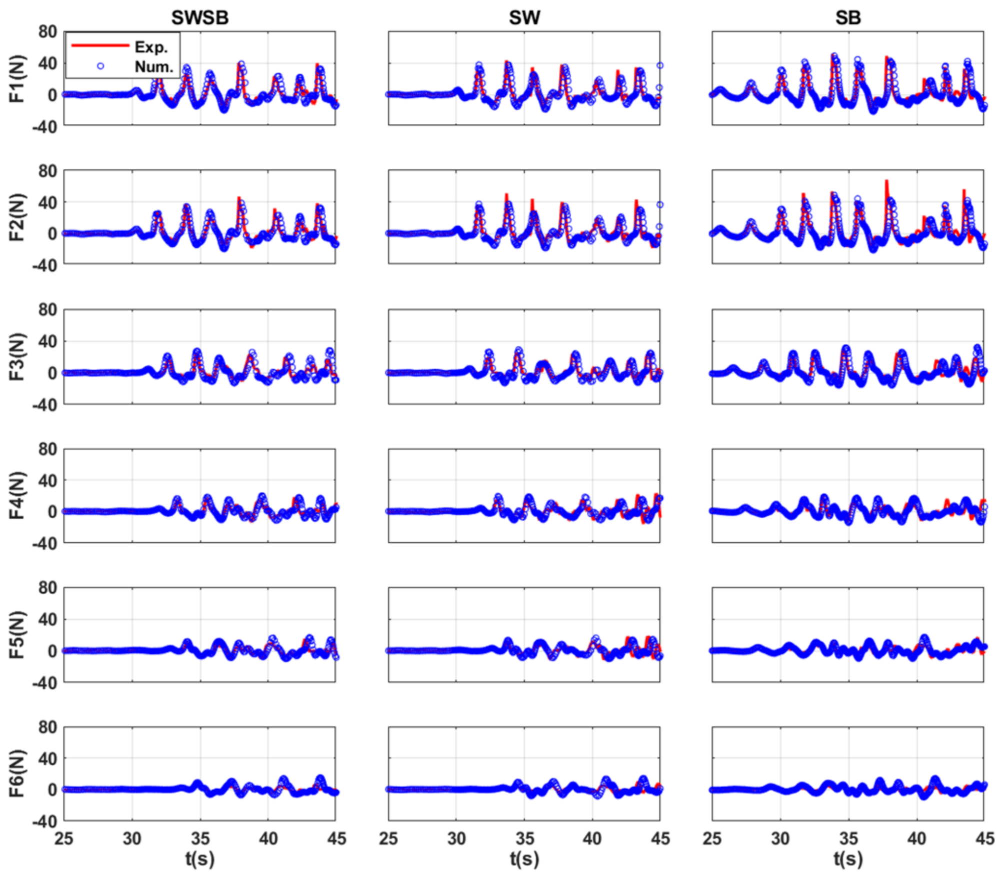

Fig. 6. Comparison of measured and simulated horizontal forces over five building rows.

representative positions, including WG1, USWG1, and ADV1. In detail, WG1 is utilized to represent the incident wave height, while USWG1 and ADV1 represent the onshore wave height and velocity measured in front of the first building row, where the intensive wave and structure interaction was observed (Figure 4). The normalized root mean square errors (*NRMSE*) and index of agreement (*IA*) were implemented to determine the correlation between measured and simulated variables [1]. The *NRMSE* quantifies the relative deviation between simulations and measurements, defined as the root-mean-square error normalized by the observed mean, while the *IA* (ranging from 0 to 1) measures the degree of model prediction accuracy, with 1 indicating perfect agreement. The NRMSE is expressed as Equation 1:

$$NRMSE = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(S_i - O_i)^2}}{O_{\max} - O_{\min}} \quad (1)$$

in which, S_i and O_i represent the simulated and observed variables at time step i, respectively, and N is the total number of data points. Moreover, the index of agreement is represented as follows:

$$IA = 1 - \frac{\sum_{i=1}^{N}(S_i - O_i)^2}{\sum_{i=1}^{N}\left(\left|S_i - \bar{O}\right| + \left|O_i - \bar{O}\right|\right)^2} \quad (2)$$

where, $\bar{O}$ is the mean of the observed parameters.

Temporal variations of measured and simulated wave height at WG1, located near the wavemaker, were compared, indicating that olaFlow accurately reproduces offshore elevations, with peak and trough differences of less than 5% and no difference can be observed for wave phases over three configurations, achieving the IA of approximately 0.94 in general (Figure 4a). The incoming wave propagated landward, experiencing shoaling over the sloping beach, and then broke in front of the first building row in the coastal berm. This breaking process is attributed to the reduction in wave height measured in USWG1. Figure 4b illustrates the time series of experimental and numerical breaking wave height. A good agreement between measured and modelled inland wave height, though slight scatters were observed in the peaks of waves. This result indicates that the model effectively reproduces the general wave height inside the constructed environment but may slightly underestimate local variations caused by turbulence and wave splashing. Cross-shore velocities are well represented, especially in the SWSB configurations (Figure 4c). Some deviations are observed in individual hard structures, which are attributed to the complex flow interactions around the first building array. Generally, the olaFlow model successfully reproduced the time histories of hydrodynamic measurements, including offshore surface elevations, inundation depths, and velocities. These results demonstrate the numerical capability to accurately capture key flow dynamics in the constructed environment. The slight deviations are attributable to wave splashing and configuration-specific effects.

Consequently, the validated olaFlow model is a reliable tool for predicting overland flow patterns in constructed coastal environments.

4.2. Validation on pressures in the first building row

Three pressure gauges (*P1* to *P3*) located in the lowest positions, directly exposed to the incident waves, were utilized to measure hydrodynamic pressures over three configurations were compared to numerical results. Figure 5 indicates that the olaFlow model replicates the time series of pressures well in terms of both pressure amplitude and frequency of pressure fluctuations. A strong agreement during the periods of peak pressure, indicating that the model accurately captures the wave–structure interaction and resulting pressure dynamics. Minor discrepancies are observed in the peak pressures of less than 10%.

4.3. Validation on horizontal forces in building arrays

Further validation was conducted to compare the time histories of horizontal forces measured by six loadcells in the first five building rows (Figure 6). Force 1 and force 2 were measured using 6DOF and LC2, located in the first building row, and exhibited a strong agreement with numerical results in peak values and force phases. The largest discrepancies occurred in the first row of the SW and SB, with underestimation of sharp impact-phase peaks attributed to complex splash-ups and air entrapment not captured by the model. To represent the impulsive forces for each wave at the SB configuration, particularly, the numerical model exhibited approximately 20% of peak values in some waves at t = 37.6 s, while a slight difference was observed from the second to fifth rows. The SWSB setup showed the best agreement in force predictions because the combined seawall and submerged breakwater effectively dissipated wave energy and smoothed flow transitions. In contrast, the SB-only case experienced stronger direct impacts and higher flow velocities due to limited energy dissipation capacity. The normalized root mean square errors (*NRMS*) ranging from 7.43% to 15.32% were observed, while the index of agreement (*IA*) was estimated from 0.74 to 0.95 over three configurations. Minor differences were observed in other structural configurations across the building arrays. This behavior is consistent with findings in previous studies [17], highlighting inherent limitations in capturing extreme localized forces during impact events. Further improvements could include finer grid resolution or multiphase modeling to better simulate these impulsive effects driven by splash and air-water interactions. Overall, the numerical model captures the main trends and peak values of hydrodynamic and loading parameters observed in the laboratory experiments, demonstrating the potential of implementing the OpenFOAM model in simulating overland flow dynamic patterns inside the coastal communities.

5. CONCLUSION

This study presents the numerical results of an OpenFOAM-based model simulating wave-driven overland flows interacting with an idealized coastal environment protected by a seawall and a submerged breakwater. The model was rigorously validated against 1:16 laboratory experiments, showing strong agreement between simulated and measured time series of offshore and onshore free-surface elevations, horizontal velocities, hydrodynamic forces, and pressures on building arrays, with normalized root-mean-square errors below 15.32% and an index of agreement up to 0.95. The results demonstrate that the olaFlow model can accurately replicate complex interactions between waves, mitigation structures, and coastal buildings, including wave shoaling, breaking, runup, and associated hydrodynamic forces. This validated numerical framework provides a robust foundation for systematically assessing the performance of coastal protection measures, such as seawalls, submerged breakwaters, and their combinations, and offers a predictive tool for designing effective flood mitigation strategies in real-world coastal communities. Further study will investigate the effectiveness of several configurations in mitigating overland flow loadings on coastal structures and flow dynamics inside the constructed environment.

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