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Berthing system in coral reef flats: hydrodynamics and design optimization

Damien SOUS [1,2], Paul GIRARDOT [1], Rémi CHEMIN [2], Serge PLANES [3,4], Anatole BRANCHARD [5], Antoine DESHOULIERES [6], Anthony MOUCHEL [7], Jean-Luc AQUA [8]

1. Université de Pau et des Pays de l'Adour, E2S-UPPA, SIAME, Anglet, France. *damien.sous@univ-pau.fr*
2. Université de Toulon, Aix Marseille Univ, CNRS, IRD, MIO, Marseille, France *sous@univ-tln.fr*
3. PSL Research University, EPHE-UPVD-CNRS, USR 3278 CRIOBE, Université de Perpignan, 66860 Perpignan Cedex, France. *planes@univ-perp.fr*
4. Université de Perpignan, 66860 Perpignan Cedex, France.
5. ODEWA, Zone de Pu'o'oro, Arue, Tahiti, Polynésie française.
6. Archipel Océanographie, Creatio Tech, 40 rue Chef de Baie, 17000 La Rochelle, France. *deshoulieres@archipel-oceanographie.com*
7. NEO4D, Immeuble Rouleau, rue Y. Martin, Papeete, Tahiti, Polynésie française. *anthony.mouchel@neosea-ic.com*
8. Direction de l'Equipement, Arrondissement Maritime, Gouvernement de Polynésie Française, 98715 Papeete, Tahiti, Polynésie française.

Abstract:
The present paper reports on a combined field and laboratory study aiming to understand and to optimize the hydrodynamical functioning of Reef Flat Docks (RFD). The in-situ measurements revealed that incoming wave height and still water level are the main driving factors for basin agitation. The laboratory experiments confirm the weaknesses of the present RFD configuration and allow to propose an optimized design, able to reduce basin agitation and setup, and currents in the channel.

Keywords:
Coral reef, Harbour, Coastal Defence, Waves, Berthing, Optimisation, Infragravity.

1. Introduction

Remote islands have always faced supply difficulties. This is particularly crucial for tropical coral atolls, which generally combines low-lying and small usable land for agriculture and infrastructure, weak financial capacities, poor local material and fresh water resources and strong remoteness from supply providers. In the worst-case scenario, no navigable passe is present in the reef barrier to allow safe berthing for boats in the main lagoon. This explains why channel-basin systems have been directly dug in reef flat, as observed for instance in many atolls in the Tuaomotu Archipelago, French Polynesia (example of Reao island in Figure 1A). While generally dangerous for boat and people, these infrastructures remain the sole entry for boat supply. Understanding the hydrodynamical functioning of such reef flat docks (hereafter RFD) is an essential step for improving their design, in the context of new infrastructure building or maintenance operation, or to predict the evolution of RFD service capacity in the context of global reef degradation (COMEAU *et al.*, 2019; CHEAL *et al.,* 2017). Unfortunately, to the author's knowledge, no engineering or research works have been dedicated to RFD systems.

An *a priori* identification of the basic processes governing the RFD hydrodynamical functioning can be gained from direct visual observations, collection of testimonies from local users and physical knowledge of coral reef wave-driven dynamics. The overall trend is that RFD are able to maintain their navigability only for small to moderate wave conditions. A rough threshold in terms of incoming wave height can be inferred from local fishermen testimonies about 1.5m, meaning that access becomes dangerous to impossible for larger waves. Illustrative snapshots are provided in Figure 1, B and C, during moderate wave conditions (wave height about 1m). The first and most critical driver of RFD is the direct exposure of their entry channel to wave breaking. The steep slope observed on forereefs often induce violent plunging wave breaking (YAO *et al.*, 2019). The presence of a channel dug into the reef flat tends to shift the breaking point landward, which often imposes on the boat pilot to surf on breaking/broken wave to enter the channel. Owing to the absence of direct protection, a large part of the wave energy is able to penetrate in the channel, only damped by breaking and frictional dissipation. The wave is partly reflected on the channel boundary/back wall, diffracted at the channel/basin angle and further reflected on each basin boundary. This complex 3D dynamics, combined higher frequency agitation and potential excitation of resonance modes (seiches), makes navigation and berthing very risky up to the final docking. The associated currents can be particularly strong in this shallow (typically 1.5 to 2m depth) and laterally constrained geometry. Due to the groupness of real irregular wave field, incoming wave energy is expected to be partly transferred to low frequency, i.e. to the so-called infragravity (IG) waves (BERTIN *et al.*, 2018). IG pulsations potentially force an additional low frequency component to the RFD agitation and current dynamics. Wave overtopping on the main basin defence wall have also been reported by local users, further contributing to agitation in the berthing basin and loading of the whole system which finally results in an increased outward flow in the channel.

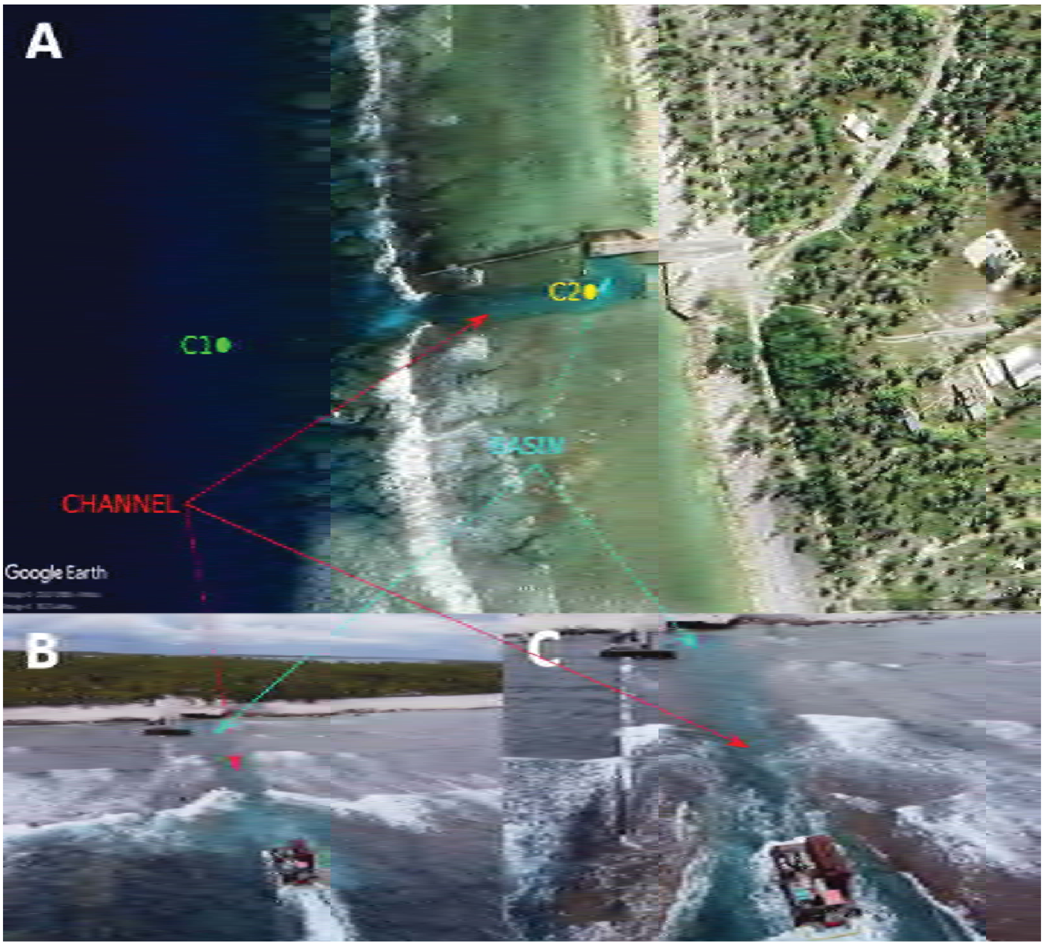

Figure 1. Aerial views of the existing RFD system deployed in Reao, French Polynesia. A: satellite overview. B and C: illustration of the boat access issue even under moderate wave conditions.

Furthermore, RFD are isolated systems, but show complex interactions with the reef flat processes. On the natural part of the reef flat, breaking wave will induce wave setup on the flat, further affected by IG-related pulsation (SOUS *et al.* 2019, SOUS *et al.* 2020). Depending on the degree of lateral sheltering by the channel side wall (one-sided wall in the Reao example shown in Figure 1), this pulsating reef-flat setup generates a lateral discharge in the channel, resulting in an additional forcing to the RFD system acting on a wide range of temporal scale.

RFD appears very complex systems in a hydrodynamical point of view, combining waves and currents over a wide range of agitation motions. However, due to the total lack of data, the previous synthesis of driving processes remains hypothetical and purely descriptive. Quantitative observations are required to better frame the governing processes, their relative magnitude and interactions and the overall response of the RFD system to variable forcing conditions in terms of waves and water levels. The objective of the present study is two-fold. First, we aim at understanding the hydrodynamical functioning of a representative RFD system, using the combination of in-situ measurements and idealized laboratory experiments. The study site is the Reao island RFD, where complete reconfiguration is planned by the Direction de l'Equipement of French Polynesia. To improve navigability, the revamp plan includes a larger basin and a deeper and larger channel, which hydrodynamical effects will be explored by the laboratory experiments. The second main objective of the study is to explore a series of optimized RFD designs potentially able to mitigate the deleterious aspects and to improve navigability and safety for boats, infrastructures and people.

2. Material and Methods

2.1 Field study

The data presented here has been recovered between May, 19 and May, 25 2023. Two bottom-moored pressure sensors have been deployed: C1 over the forereef and C2 in the basin, in 11 and 3m depth, respectively (Figure 1A). Pressure data were recorded continuously at 1Hz. Significant wave height was estimated from the pressure spectra based on linear wave assumption (correction factor limited to 50 in high frequency). Three frequency bands were distinguished:

- Infragravity waves (IG) for F<0.04Hz.
- Short waves (SW) for 0.04<F<0.25Hz.
- High frequency waves (HF) for F>0.25Hz.

2.2 Laboratory experiments

The experiments were performed in the SEATECH-MIO wave basin, 8m long, 2.8m wide (Figure 2). A base bathymetry has been used for each experiment, see Figure 2B. It represents an idealized view of fringing reefs. The waves first propagate over a 3.5m long flat bottom section before reaching the linearly sloping forereef (1:2.5) and the reef flat (2m long, 0.8m above the basin bottom). Aiming to represent an idealized version of the natural reef system, a reef crest (0.8cm high, 28cm long) has been included at the seaward limit of the reef flat. A linearly sloping beach (1:5) was then deployed at the landward end of the reef flat, equipped with rough plastic plates to improve dissipation. The rest of the reef flat remained smooth in order to facilitate the switch between configurations.

The scaling ratio are 1/30 and 1/80 along the vertical and horizontal directions, respectively. The wave features and the model dimensions have been designed to preserve correct similitude in the physical processes involved in the wave transformation, in particular the wave steepness parameter (0.01<ka<0.2) in deep water and the shallowness parameter (0.001<kh<0.02) on the reef flat.

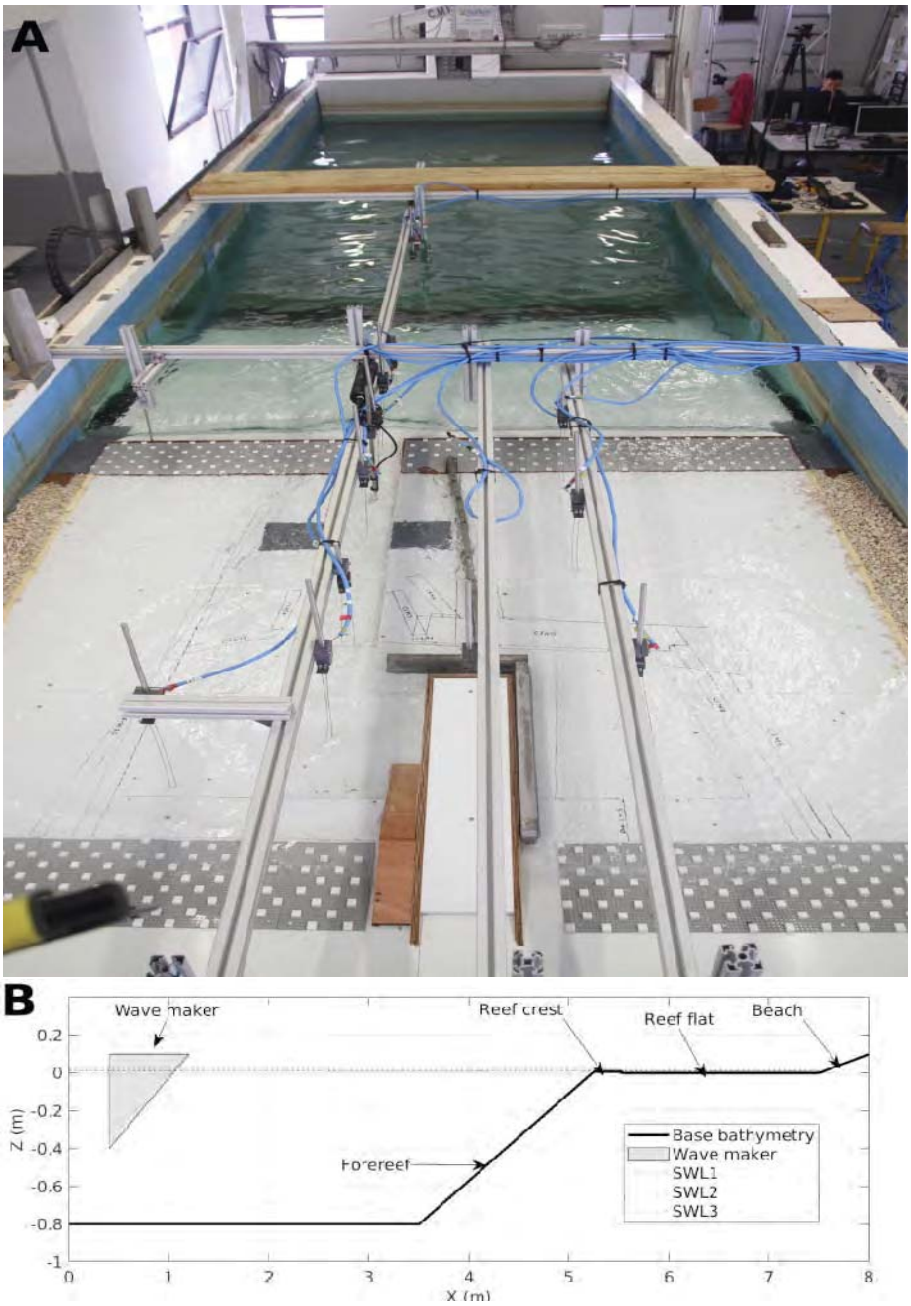

Figure 2. Laboratory experimental setup. A: Overview of the wave basin, with waves propagating from top to bottom. B: Cross-shore profile of the base bathymetry.

Four RFD configurations have been tested (Figure 3):

- RFD1, which corresponds to a simplified design of the present configuration at Reao.
- RFD2, which corresponds to the first project design including in particular (i) a widening and deepening of both channel an basin to ease navigation, (ii) symmetrical defences along the channel, higher than the single one existing for

RFD1 and closely attached to the channel output in order to minimize the entry of wave energy, (iii) a larger and wider frontal stepped seawall protecting the basin following previous study (ROSSIGNOL & SOUS, 2022) and (iv) a dissipative riprap at the channel end.

- RFD3, based on RFD2 design with the inclusion of symmetrical resonating basins along the channel designed following the specifications of the Wave Filter Theory (NAKAMURA *et al.*, 2007).
- RFD4, based on RFD3, replacing resonating basins by secondary diverging walls.

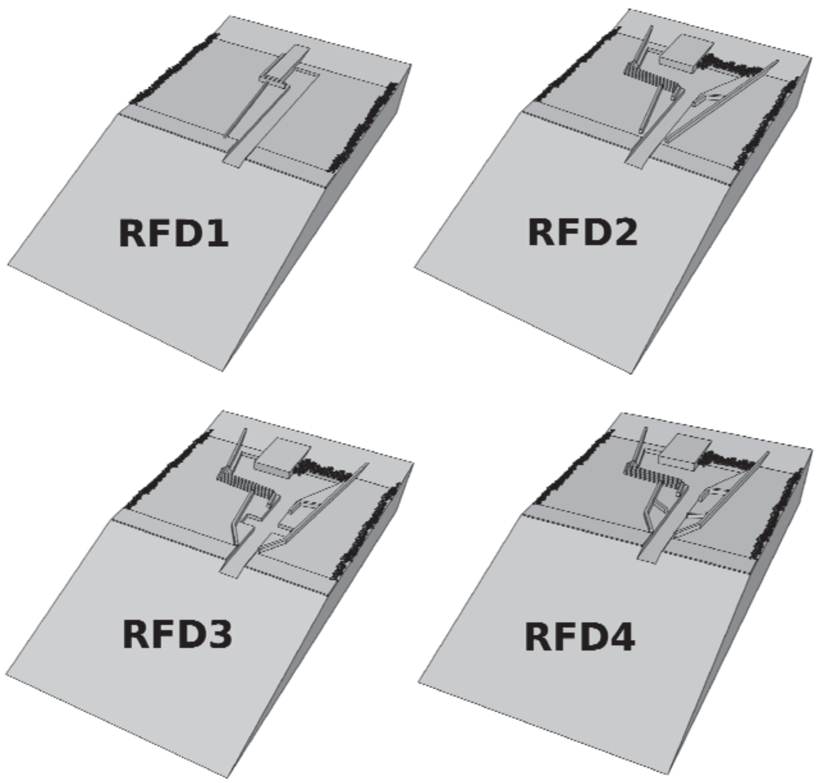

Figure 3. Laboratory experiments: description of the tested configurations.

Fourteen wave gauges were deployed to track free surface elevation from deep water to the basin. The sampling frequency was 100Hz. An acoustic Doppler current meter was deployed in the channel, 2cm above the bottom. Two still water level conditions were tested at 1 and 2cm above the reef flat elevation, named high and low water conditions, respectively. For each RFD and each water level, twelve regular wave conditions, with wave height from 2.7 to 10.6cm and period from 0.9 to 1.5s, have been tested to decipher the base hydrodynamic response of the system. One irregular wave case, with significant wave height 8cm and peak wave period 1.05s (JONSWAP spectrum) has been tested to analyse the RFD behaviour under more natural forcing, allowing in particular to study the wave-group-driven IG signal.

3. Results

3.1 Field observations

Figure 4 displays the significant wave heights measured at C2 (basin) in the three selected band vs the incoming short-wave energy flux at C1 (forereef). The measurements reveal that (i) each wave component increases with incoming energy, (ii) the basin is dominated by IG fluctuations while SW and HF heights display a similar contribution, about 1/3 of the IG wave height, (iii) SW and HF components are affected by water depth, with higher agitation at high tide, while the IG wave height is weakly affected by the water depth.

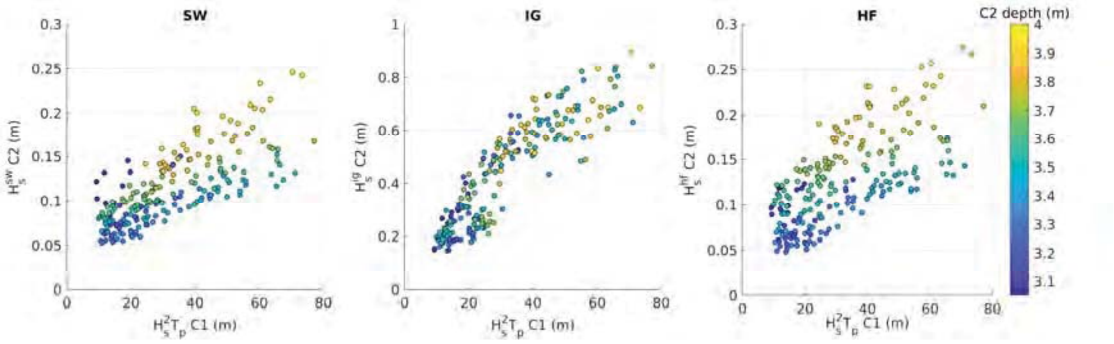

Figure 4. In-situ experiments. Significant wave height in SW, IG and HF bands at the basin sensor vs incoming SW energy flux at the forereef (basin depth as color level).

3.2 Laboratory results

Figure 5 displays the analysis of the laboratory measurements. We first analyse the reference RFD1 as the reference configuration (black dots in Figure 5). Basin and channel agitations show a straightforward dependency on the incoming wave energy, as observed during the field study. The time-averaged current is maximal for moderate wave conditions and tends to reach a lower and nearly stable value for high incoming energy. This peculiar response cannot be directly explained using the single near-bottom measurement point available here. The current fluctuation, i.e. the standard deviation of the current signal, increases with incoming wave energy until a stable regime is reached for large wave conditions. The basin setup shows a regular increase with incoming wave energy, being of the order of 30 to 40% of the deep-water wave height. The main findings are now interpreted in terms of RFD design performance with respect to RFD1, i.e. the present reference configuration at Reao.

- RFD2 induces a general increase of 20 to 35% of the wave height in the channel, most likely due to the channel deepening and widening which allows more wave energy to propagate. By contrast, the SW agitation is reduced by about 25% in the basin, revealing in particular the sheltering effect of the lateral channel walls. RFD2 is also associated to a decrease of the time-averaged return flow in the channel for

small and moderate wave conditions. For the largest wave conditions, the return current appears to be weakly affected by the new configuration. The current fluctuations remain nearly unchanged whatever the wave conditions. The basin setup, i.e. the rising of the mean water level with respect to the offshore level, is reduced by 10% compared to RFD1. For the irregular wave cases, the IG wave height is strongly attenuated (about 60%) by RFD2 configuration.
- RFD3 displays very similar response w.r.t RFD2, showing no straightforward improvements related to the installation of resonators.
- RFD4 displays significant improvements w.r.t RFD2, with further reduction of the basin agitation for nearly all wave conditions, and reduction of channel agitation and basin setup for high energy conditions. This effect is mainly attributed to the two rows of diverging walls which allows a progressive weakening of the wave front during its propagation into the channel.

4. Discussion

The present study aimed to improve our knowledge of the functioning of RFD systems. As expected from existing knowledge on natural fringing reef systems, the level of wave energy reaching the basin excavated in the back reef is primarily controlled by the incoming wave height and the still water level. After propagation over the forereef and throughout the access channel, spectral transfers redistribute the main part of the incoming SW energy to IG pulsations. The typical periods of IG observed in the basin range between 150 and 1000s. Considering the typical length (140m) and depth (2m) of the channel, the higher part of the observed IG band may correspond to semi-open seiching modes of the channel, but the main part of the energy is measured at much lower frequencies, more likely corresponding to direct wave-group forcing for the long period swells (14-21s) present during the field experiment. It should be emphasized that for similar sites exposed to shorter swells, the wave-group energy fluctuations can match the channel seiching period and lead to damaging resonance. Similarly, as accounted for in classical harbour design, the basin typical dimensions must be chosen so as to avoid resonance in the SW range. Higher frequency agitation has also been observed, likely due to the combined effects of direct transfers from the incoming SW to higher harmonics and the multiple interactions between waves and obstacles in the RFD system. Classically, the overall recommendation to reduce wave agitation is to maximise wave dissipation wherever possible, using ripraps, porous or sloping walls instead of vertical impervious ones.

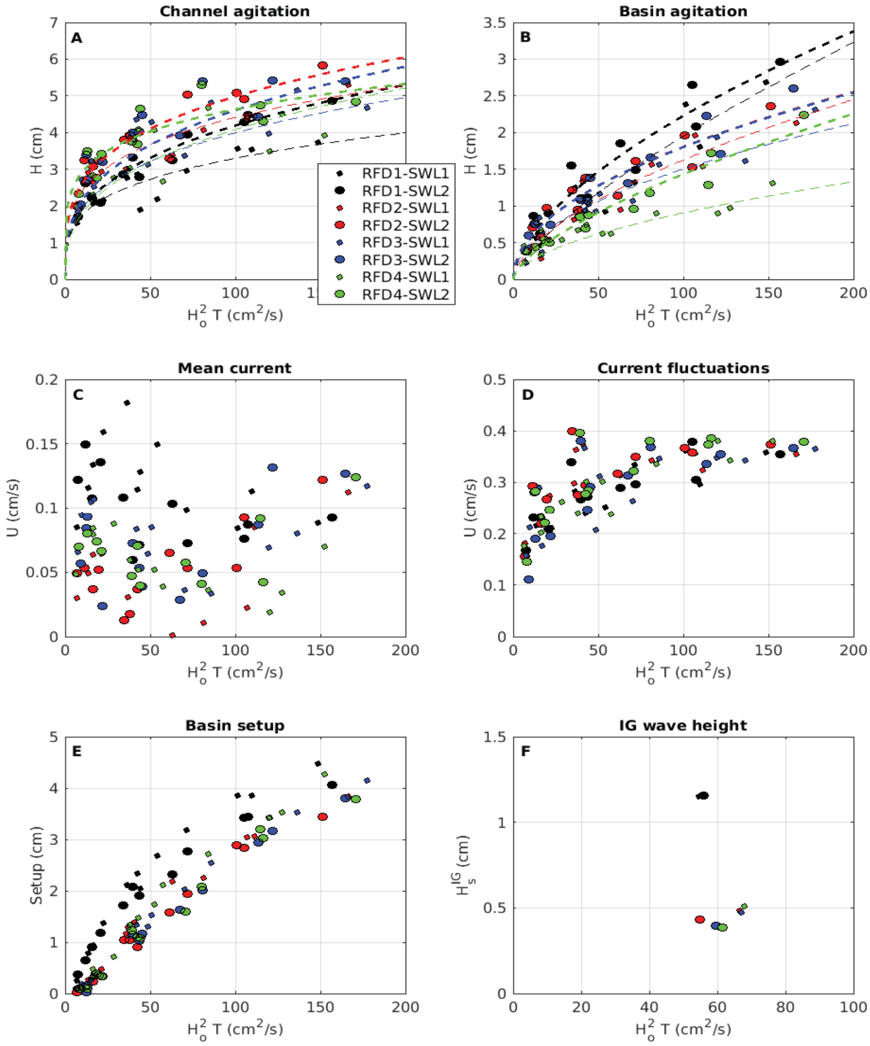

Figure 5. Laboratory experiments. Chanel wave height (A), basin wave height (B), time-averaged channel current (C), channel current variance (D) and basin setup (E) vs incoming energy flux for the regular wave conditions. Large/small dots display high/low water levels. Thick/thin dashed lines denote corresponding trends for high/low water levels, respectively. F: basin IG wave height for the irregular wave forcing cases.

The laboratory experiments allowed to help in the design optimization for the new RFD at Reao island. However, the limitations of physical modelling should be kept mind before any direct application. Due to the cost of laboratory experiments, a limited number of models have been tested and better untested solutions may exist. Most of the experiments have been focused on regular wave conditions with a simplified design in order to better understand the fundamental behaviour of the system. The complexity of the real system, involving a number of feedbacks, may show significant departures from the idealized laboratory experiments.

5. Conclusions

The present study is dedicated to the channel-basin berthing systems built on coral reef flat in remote tropical islands, referred here to as Reef Flat Docks. Basin on field and laboratory experiments, the first aim is to gain understanding of the hydrodynamical functioning in terms of basin agitation and channel current under different wave and water level conditions. The second aim is to optimise the RFD design through the comparison of different RFD configurations with the physical model. The maximal sheltering efficiency is reached with a configuration combining symmetrical lateral defences along the main channel, including two rows of divergent walls.

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