Innovations Deserving Exploratory Analysis Programs

NCHRP IDEA Program

SEAHIVE - Sustainable Estuarine and Marine Revetment

Final Report for
NCHRP IDEA Project 213

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SEAHIVE - Sustainable Estuarine and Marine Revetment

IDEA Program Final Report

Project NCHRP IDEA-213

Prepared for the IDEA Program
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The National Academies of Sciences,
Engineering, and Medicine

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The SEAHIVE IDEA Project has been one of those research projects that transcend their original monetary value, not only because of the pilot installations that were secured in collaboration with local municipalities, but also for the research connections and the product's potential as a green engineering paradigm of coastal protection. A heartfelt thank you to Expert Advisory Panel members Steven Nolan, Florida Department of Transportation, who was at the foundation of this project sharing his ideas, and Eric Anderson, Palm Beach County, whose efforts in technology transfer and dissemination helped the PIs secure the Wahoo Bay pilot installation and make connections with local stakeholders, professionals, and other State officials. Finally, the PIs would like to also thank the NCHRP IDEA Program Manager, Dr. Inam Jawed, for his constant support and understanding throughout this period, especially during the COVID-19 pandemic.

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EXECUTIVE SUMMARY

With coastal population density always growing and average annual temperatures projected to also increase, coastlines will likely experience stronger storm events and potentially more devastating disasters. These events include tropical cyclones and hurricanes, which bring extreme winds, rain, storm surge, and waves to the built environment and coastal infrastructure. Storm surge and wave action induce destructive forces to coastal communities that can result in loss of life, shoreline erosion, as well as structural damages to the built environment and infrastructure such as the transportation network. This includes more than 60,000 miles of coastal highways that have been periodically exposed to coastal flooding. Coastal routes and protective structures, such as revetments and seawalls, serve as barriers against storm flooding and wave action. However, traditional shoreline protection structures like seawalls do not dissipate wave energy; they reflect waves creating more turbulent conditions which make sites and their surroundings more susceptible to damage. Moreover, they typically do not provide a hospitable environment for biodiversity.

The objective of the SEAHIVE IDEA project has been the research and development of a sustainable estuarine and marine revetment system. The system's development has been on the basis of physical testing at the University of Miami SUrge STructure Atmosphere INteraction (SUSTAIN) Facility and morphological considerations. First, a morphological investigation on the cross-sectional profiles for the elements composing the system was conducted considering geometrical properties as well as other aspects such as element manufacturing. SEAHIVE prototype elements of the three different cross-sectional profiles with varying perforation configurations were fabricated and tested experimentally at the SUSTAIN Facility under different water/waves conditions defined through a dimensional analysis of the Froude number. The envelope pressure profiles were found to vary significantly between prototype elements with the different cross-sectional profiles, the void configuration (i.e. the number, size and position of the perforations) and the water/wave condition considered. Considering the interlocking of hexagonal units and that they maximize the volume for a given amount of material similar to a beehive, hexagonal units were selected for the system design. System-design testing focused on the hydrodynamic performance of a cluster of SEAHIVE units starting with the testing of a vertical SEAHIVE wall section in the SUSTAIN wind/wave tank. For this phase of the testing, the analysis was conducted on the basis of the water-level measurements as they allow to characterize the performance of the system through estimates of wave reflection and wave-energy dissipation. The comparison of the reflection coefficient between the vertical SEAHIVE system model with a solid vertical wall model revealed that the SEAHIVE system model decreases significantly wave reflection while also dissipating more energy. Tests conducted on horizontal SEAHIVE system configurations revealed that the system performs also well in other contexts from riprap to submerged breakwater/reef applications.

The versatility of the SEAHIVE system allows it to be used in a variety of projects. With the help of the IDEA expert panel and the support of the FDOT, the PIs have secured three pilot installations in Southeast Florida. The first one is a riprap installation in collaboration with the City of North Bay Village. The second one is in partnership with the City of Miami Beach and in the context of a University of Miami Laboratory for INtegrative Knowledge (U-LINK) project where SEAHIVE will be used as a hybrid artificial coral reef. The third application is a seawall/mangrove planter in collaboration with Shipwreck Park (a non-profit organization), the City of Pompano Beach, and Broward County in relation with the establishment of an educational marine park named Wahoo Bay (Figure 1) partially funded by the Florida Fish and Wildlife Conservation Commission (FWC). All installations are underway and will be monitored to assess the ecological and engineering performance of the system, as well as to acquire important techno-economic data for further developments.

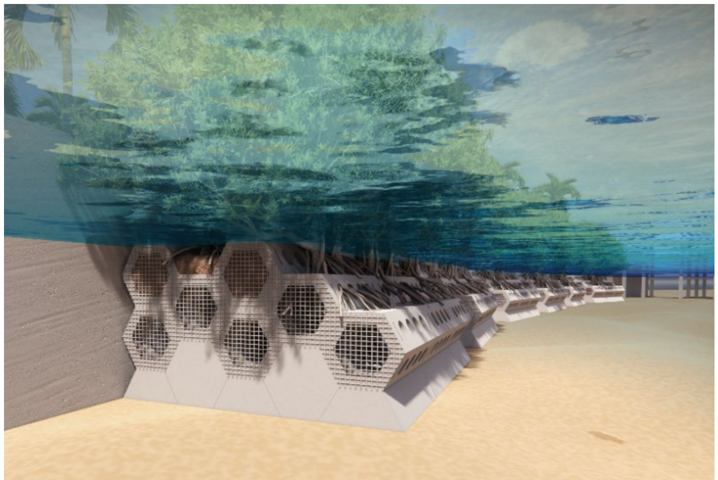


FIGURE 1 Rendering of the Wahoo Bay SEAHIVE system. Credit: D. Jalfon, University of Miami

Laboratory tests on SEAHIVE models have shown that the system provides better protection against storm surge and wave action than traditional coastal protection structures such as vertical seawalls and trapezoidal submerged breakwaters. Perforations on the side faces of SEAHIVE units form interconnected channels allowing water flow under surging or breaking waves and dissipating wave energy through turbulence. Moreover, the structural complexity of the system provided by its faceted perforated geometry combined with the use of ecofriendly materials is expected to increase the system's biocompatibility and potential for habitat creation. It should be noted that SEAHIVE elements are being manufactured using biophilic concrete mixtures and non-corrosive reinforcements minimizing environmental impacts and extending service life. Moreover, manufacturing is conducted using traditional concrete pipe casting techniques. Considering the adaptive features for various applications and topography, as well as its potential for habitat creation, the SEAHIVE system provides an efficient and cost-effective eco-engineering alternative for the protection of the transportation network and the built environment in coastal communities that can be tuned for both low and high energy areas. The system has thus received significant media attention from both local and national channels including a segment in Weather Underground by the Weather Channel. With the cost of coastal protection in the United States projected to skyrocket to $400 billion by 2040 according to the Center for Climate Integrity, the proposed system presents a great payoff potential.

IDEA PRODUCT

The product of this IDEA project is called SEAHIVE™ and it is an engineered marine and estuarine protection system that dissipates wave energy and creates habitat. The geometry of the system mimics nature providing passage to water dissipating energy within the structure. The structural complexity of the system combined with the use of biophilic materials also increases the potential of the system for habitat creation [1]. Moreover, the system can be adapted to the site conditions providing a versatile marine and estuarine protection that can be used by transportation agencies to protect coastal communities and their infrastructure.

The Southeast United States is home to over 70 million people and includes 29,000 miles of coastline. With coastal population density in the U.S. as a whole and in the Southeastern region always growing and average annual temperatures projected to also increase, the coastline will likely experience stronger storm events and potentially more devastating disasters. These events include tropical cyclones and hurricanes, which bring extreme winds, rain, storm surge, and waves to coastal communities (Figure 2). As identified by the National Research Council [2], there are more than 60,000 miles of coastal highways already exposed to periodic coastal storm flooding and wave action [3]. There is thus a great need to explore effective yet cost-efficient methods that decrease the impact and risk associated with storm surge and waves to transportation infrastructure and the built environment in general.

FIGURE 2 Photo from the City of Miami during hurricane Irma. Source: www.abcnews.com

Seawalls are a common hard solution utilized to improve infrastructure and community safety in the face of high-intensity storms and flooding. However, traditional seawall structures do not dissipate wave energy; they reflect back waves creating more turbulent conditions which make sites and their surroundings more susceptible to erosion and damage. Moreover, they typically do not provide a hospitable environment for biodiversity; seawalls on average support 23% lower biodiversity and 45% fewer organisms than natural shorelines [4]. Conversely, "living shorelines" are often considered as the ideal ecofriendly protection barrier. Although they are a natural and cost-effective barrier, living shorelines are not generally applicable in areas with small footprint availability and/or harsh wave conditions and high storm surges. In such areas, improvements over traditional solutions in both hydrodynamic and ecological performance are possible with novel green engineering solutions such as SEAHIVE.

CONCEPT AND INNOVATION

The SEAHIVE IDEA project focused on the research and development of a novel engineered marine and estuarine protection system that dissipates wave energy and creates habitat. The system's development has been on the basis of physical tests at the University of Miami SUrge STructure Atmosphere INteraction (SUSTAIN) Facility. The SUSTAIN Facility (Figure 3) can generate directionally varying waves using a 12-paddle system combined with direct wind forces simulating hurricane conditions up to a Category 5 hurricane on the Saffir-Simpson scale. Moreover, with a tank size of 23 m × 6 m × 2 m, SUSTAIN allows physical testing at near-full-scale conditions. Testing in SUSTAIN provides a unique opportunity to experimentally evaluate the performance of the SEAHIVE system prior to its full-scale implementation.

FIGURE 3 The University of Miami SUrge STructure Atmosphere INteraction (SUSTAIN) tank.

The testing of SEAHIVE system models in the SUSTAIN Facility revealed that the system induces less wave reflection and higher wave energy dissipation compared to a traditional solid vertical revetment with the exact values depending on the water/wave conditions and the configuration of the system. Considering the system's engineering performance as shown through the physical testing in SUSTAIN, combined with its potential for biocompatibility and habitat creation provided by its faceted perforated geometry and the use of ecofriendly materials, SEAHIVE presents a novel modular, cost-effective yet efficient and ecofriendly marine and estuarine protection system that can be used to the transportation network and the built environment in coastal communities that can be tuned for both low and high energy areas. It should be noted that SEAHIVE elements will be manufactured using biophilic concrete mixtures and non-corrosive reinforcements. For the biophilic concrete mixtures, the PIs have been coordinating with other researchers from the University of Miami including Drs. Prannoy Suraneni and Kathleen Sullivan Sealey, experts on cementitious materials and marine biology, respectively, who have been performing auxiliary tests on cement biocompatibility. Moreover, with the help of the IDEA expert panel and the support of the FDOT, three pilot SEAHIVE installations were secured in South Florida, that will be used to monitored to assess the ecological and engineering performance of the system under real conditions, as well as to acquire important techno-economic data for further developments as well as for deployment of the product to the practice. Figure 4 illustrates the timeline and milestones of the SEAHIVE IDEA project.

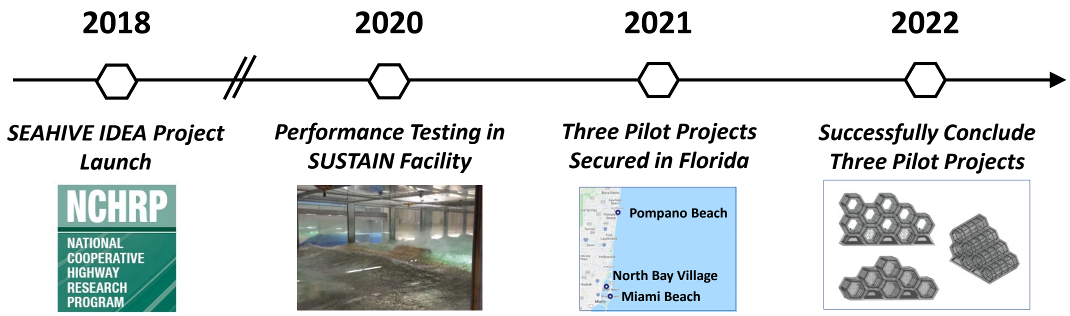


FIGURE 4 Illustration of the timeline and milestones of the SEAHIVE IDEA project.

The innovation of this project lies thus at the proposal of a versatile protective green engineered system that has been experimentally validated through laboratory testing under varying water/wave conditions. The engineering and ecological monitoring of the pilot installations that are currently in progress and include the implementation of the system in three different sites considering three different applications will also contribute to this effect. In terms of payoff this project features a synergistic collaboration among an interdisciplinary team of experts from the University of Miami, local stakeholders, professionals and government officials as well as professionals from the precast industry. Figure 5 shows the first SEAHIVE elements produced. It should be noted that the PIs have received inquiries about the commercialization of the system with the University of Miami and the research and development team holding the rights to intellectual property to UMIP-453 “SEAHIVE”. With approximately 3,500 miles of concrete bulkheads and seawalls in Florida and estimated costs of basic coastal and tidal protection for Florida alone expected to reach $76 billion statewide in the next 20 years [5], the proposed system can thus be of a great economic benefit while minimizing negative environmental impacts

FIGURE 5 Photos of SEAHIVE units at the manufacturing facility in Florida.

INVESTIGATION

The investigation of the SEAHIVE system started by a morphological investigation on the cross-sectional profiles to be used for the elements composing the system considering geometrical properties as well as other aspects such as element manufacturing. Elements with circular, square and hexagonal cross-sectional profiles were thus considered. Elements with circular cross-sectional profiles are commonly used in construction with applications varying from concrete piles to pipes. They are thus relatively easy to manufacture and install. Elements with square cross-sectional profiles were considered as a modular way of obtaining straight and/or stepped surfaces, while elements with hexagonal cross-sectional profiles were considered for the geometrical/morphological properties of the hexagonal shape (hexagons along with triangles and squares are the only shapes that can provide continuous tessellations of a surface with hexagons also maximizing the volume for a given amount of material). SEAHIVE prototype elements of circular, square and hexagonal cross-sectional profiles with varying perforation configurations were thus fabricated and tested experimentally at the SUSTAIN Facility (Phase I).

For each cross-sectional profile (circular, square and hexagonal), five prototypes with varying perforation configurations were investigated. The perforation configurations included a solid element of reference, as well as two elements with 20 perforations in total (five on each side) with perforation having diameters of either 0.075 or 0.130 m. The number of perforations and maximum perforation diameter was decided so that the minimum distance between vertically stacked perforations is at minimum equal to the perforation diameter avoiding thus stress concentrations and promoting ease of fabrication for SEAHIVE elements made out of reinforced concrete. The remaining two prototypes included variants developed considering the same ratio of void wall surface over solid wall surface with the prototype element having 20 perforations with a 0.130 m diameter. The number of perforations on the elements thus varied in these elements. Table 1 presents all prototype configurations, while Figure 6 shows a series of perforated SEAHIVE elements in front of the SUSTAIN tank.

TABLE 1 Element prototypes with different cross-sectional profiles and perforation configurations.

Cross-sectional profile dimensions	Perforation diameter (m)	Void wall surface over solid surface
Circular (d_c = 0.3 m)	No perforation	0%
	0.130	20%
	0.075	10%
	0.075	21%
	0.075 and 0.13	23%
Square (d_s = 0.3 m)	No perforation	0%
	0.130	17%
	0.075	8%
	0.075	19%
	0.075 and 0.13	17%
Hexagonal (d_h = 0.2 m)	No perforation	0%
	0.130	18%
	0.075	9%
	0.075	20%
	0.075 and 0.13	17.5%

Phase I of the project focused on the individual testing of the prototype SEAHIVE elements in the SUSTAIN tank. SEAHIVE prototype elements were instrumented with pressure sensors on their walls, fixed in the tank with an auxiliary support system and tested under varying water/wave conditions. Other measurements included water velocity and level before, inside and after the elements. In order to improve the pressure data acquisition a Scanivalve MPS4264 64-channel miniature Ethernet-based pressure scanner was purchased with the cost covered by the PIs. The testing conditions were defined based on wave-history data from four U.S. locations (zones). Wave data was explored to define similarity between prototype structures in the selected locations through a dimensional analysis of the Froude number and a geometrical scale of 1/5. Table 2 lists the SEAHIVE experimental conditions that were considered for Phase I testing.

FIGURE 6 Element prototypes with different cross-sectional profiles and perforation configurations in front of the SUSTAIN Facility.

TABLE 2 Overview of SEAHIVE test conditions in Phase 1.

Parameter	Conditions	No. of conditions
Wave Period (Sec)	1 (short); 1.5 (medium); 3 (long)	3
Wave Height (m)	0.10 (low); 0.20 (medium); 0.30 (high)	3
Irregular Waves	JONSWAP spectrum ($H_s = 0.20\ m$, $T_d = 1.5\ sec$)	1
Water Depth (m)	0.45 (shallow); 0.75 (deep)	2
Cross-sectional Profile	Circular; Square; Hexagon	3
Void Ratio	Solid; Low; High (three configurations)	5

Phase I data analysis focused on exploring pressure and water-level measurements in an effort to understand and quantify the influence of the cross-sectional profiles and perforation configurations on wave action. Figure 7 presents the experimentally defined envelope pressure profiles for the square cross-sectional prototype elements which served as reference for the different comparisons, while Figures 8 and 9 show the pressure profiles for circular and hexagonal elements. As expected, solid elements were found to sustain higher pressures compared to perforated elements. This is due to an increased wave reflection in front of the elements and the absence of wave transmission through them. However, the envelope pressure profiles were found to vary significantly between prototype elements with different cross-sectional profiles, the void configuration (i.e. the number, size and position of the perforations) and the water/wave condition considered. Moreover, some measurement reliability issues were also identified as pressure measurements under wave action i.e. under the alternating action of wind and water pressure seem to include errors. It is thus advised that future studies focus on measuring the related forces through the use of load cells

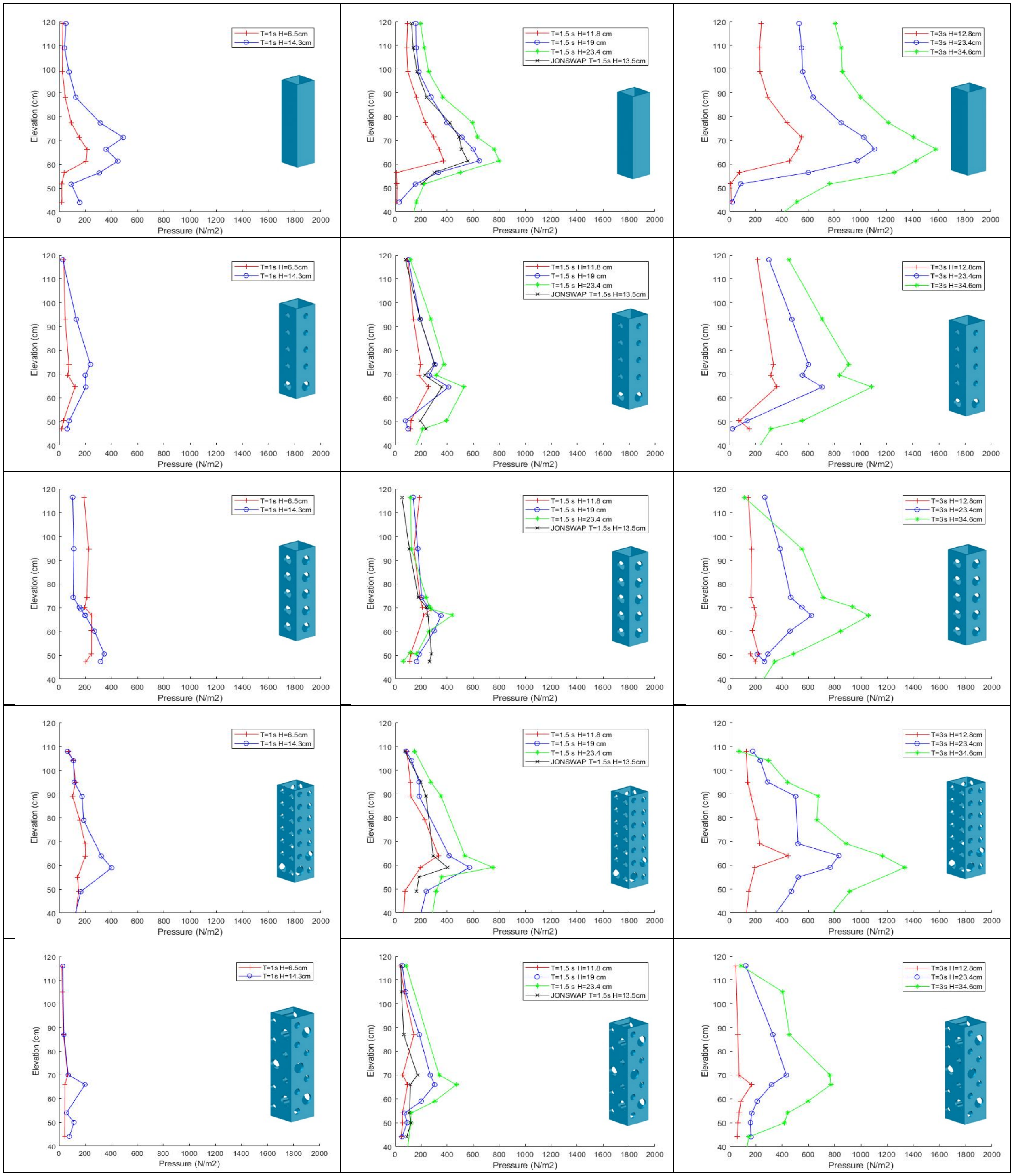


FIGURE 7 Experimentally defined wave-pressure envelopes for square cross-sectional elements.

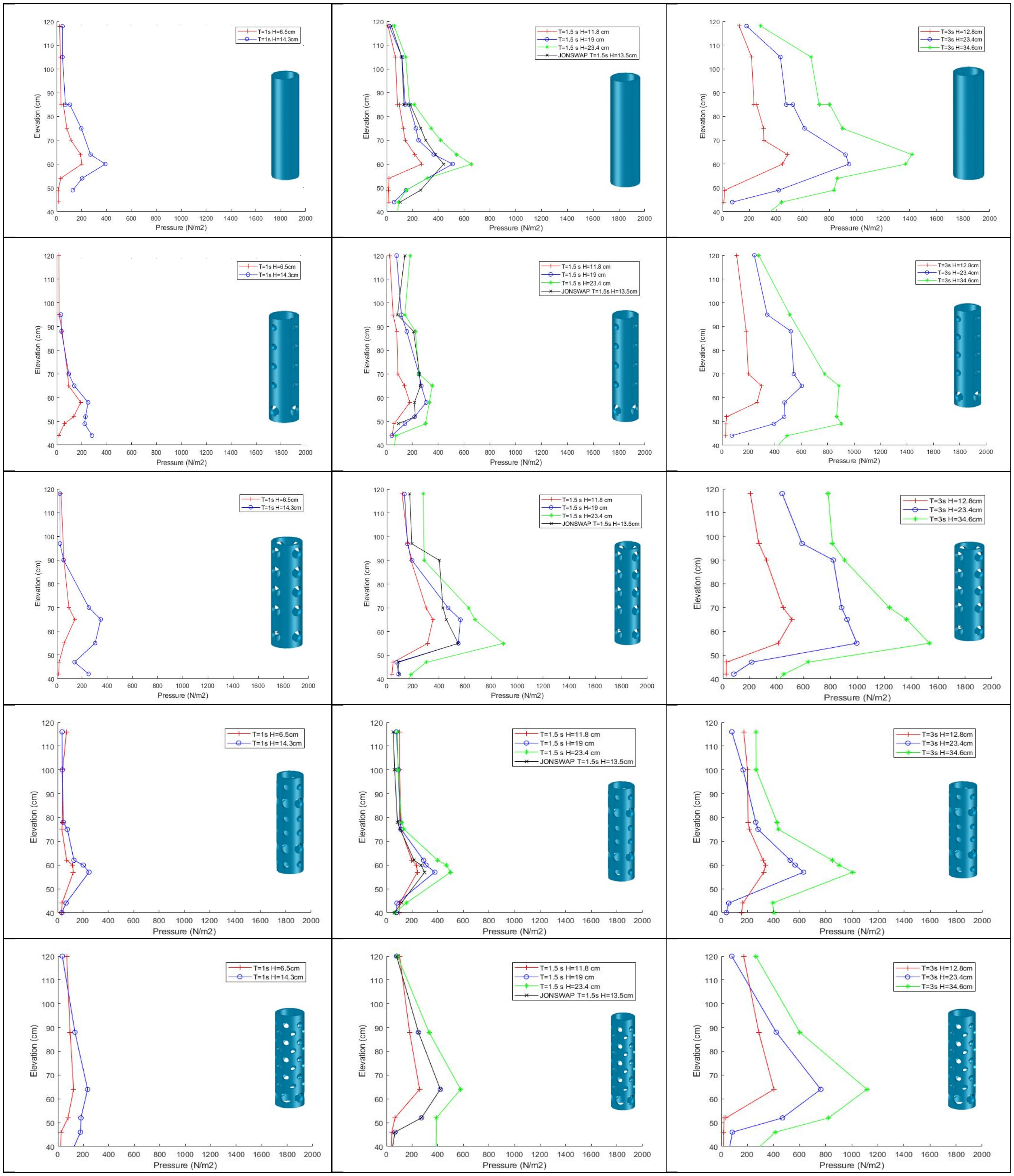


FIGURE 8 Experimentally defined wave-pressure envelopes for circular cross-sectional elements.

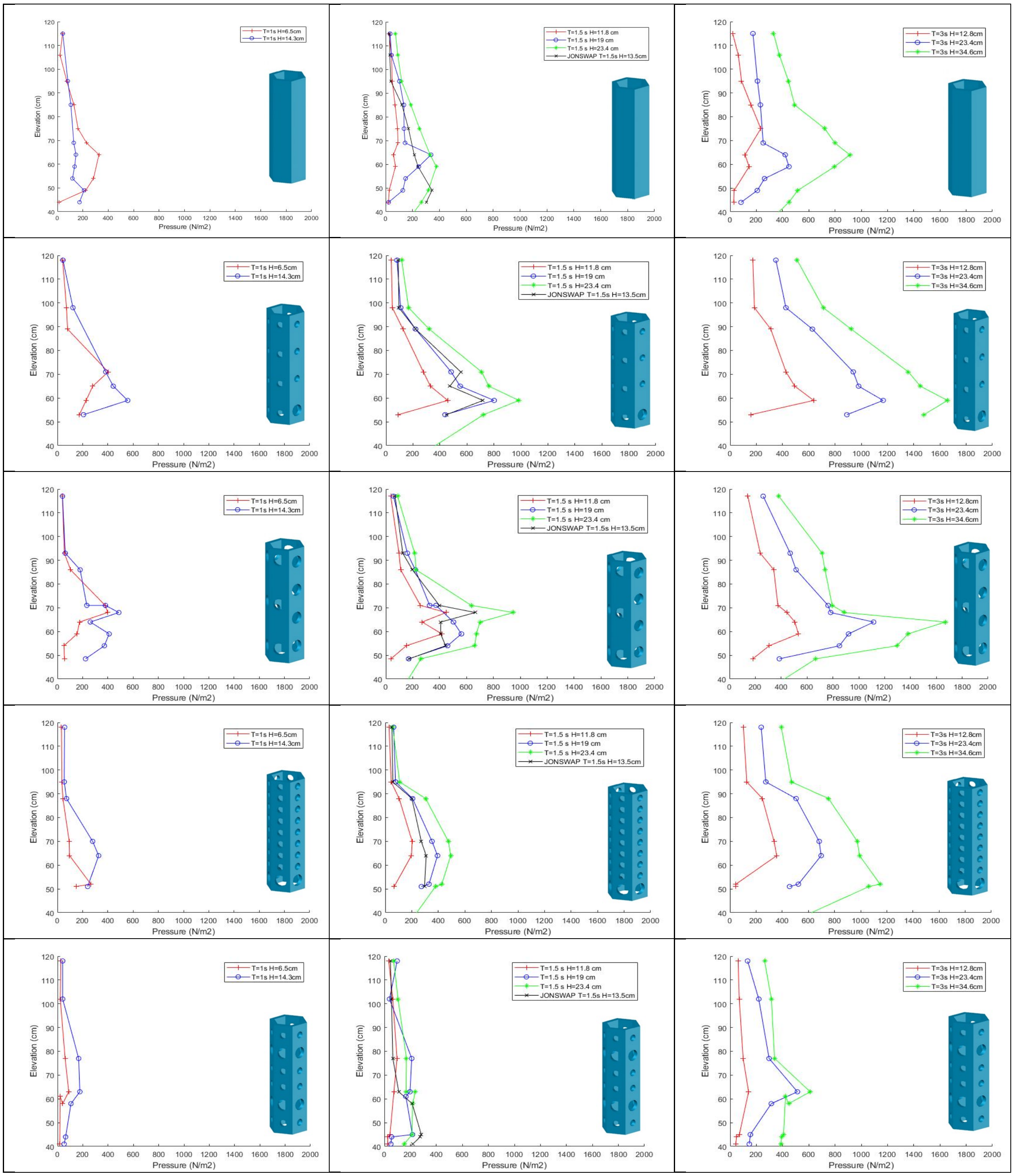


FIGURE 9 Experimentally defined wave-pressure envelopes for hexagonal cross-sectional elements.

Phase II of the project focused on the performance of the SEAHIVE system with the testing of a vertical SEAHIVE wall section in the SUSTAIN wind/wave tank. The system model was composed of 15 SEAHIVE elements with hexagonal cross-sectional profiles configured in three rows of five elements. The elements were fabricated out of wood having a circumscribed theoretical diameter of 0.40 m (hexagonal side length of 0.20 m) and varying heights of approximately 0.35 m, 0.635 m and 1.00 m. Figure 10 illustrates the experimental set-up for the Phase II testing in the SUSTAIN tank. Similar to the previous phase, the experimental set-up included a series of pressure and water-level measurements. However, for this phase the focus shifted on the water-level measurements as they allow to characterize the performance of the system through the calculation of wave reflection, wave transmission (for fully perforated configurations only) and wave-energy dissipation. Water-level measurements were conducted using a combination of Ultrasonic Distance Meters and Wave Wires at a frequency of 20 Hz with three measuring points before and after the SEAHIVE model.

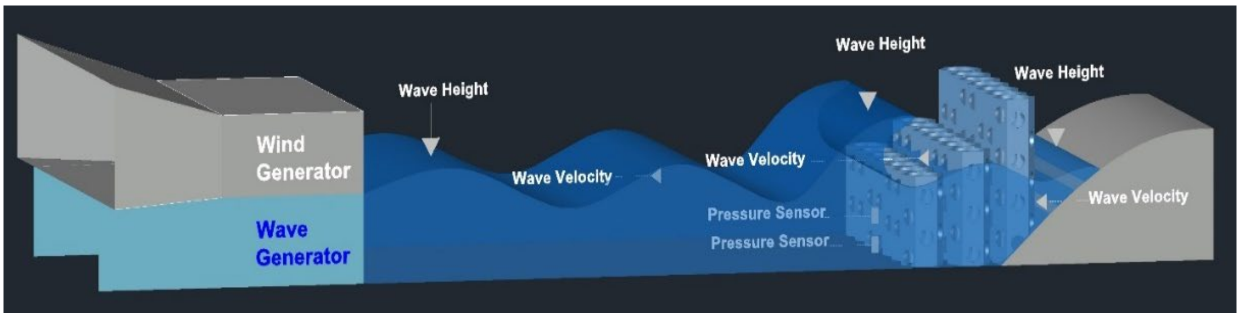


FIGURE 10 Illustration of the physical testing of the SEAHIVE system in the SUSTAIN tank.

Three system perforation configurations were considered in this phase of the testing: a) a solid configuration, b) a semi-perforated configuration, and c) a fully perforated configuration. The solid configuration was studied to understand the effects of system's geometry on waves. In the semi-perforated configuration, only the first two rows had perforations along the length of the elements with the first row having large perforations (perforation diameter of approximately 0.13 m), while the second row has small perforations (perforation diameter of 0.075 m). No perforations were included in the third row. This semi-perforated configuration (Figure 11) was studied for revetment applications investigating the progressive absorption of the wave energy within the SEAHIVE system. In the fully perforated configuration, all elements have large perforations allowing the investigation of wave transmission through the system for other applications.

FIGURE 11 Semi-perforated SEAHIVE system model configuration in SUSTAIN.

It should be noted that two sections of a solid vertical wall made of wood were also constructed and placed adjacent to the SEAHIVE model to reduce the testing surface and provide data for comparison with a vertical non-perforated (solid) structure. Figure 12 illustrates the different system perforation configurations considered.

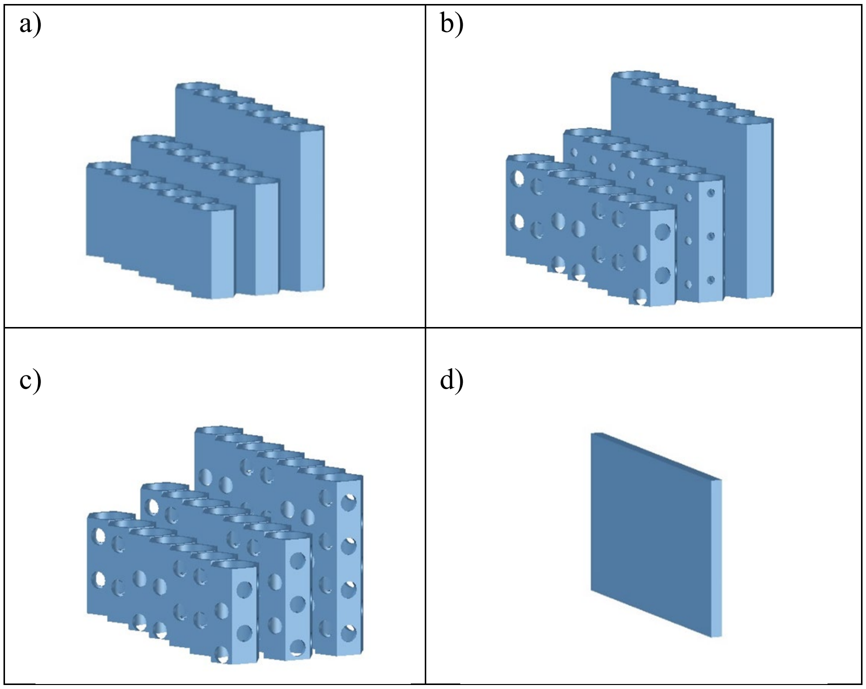


FIGURE 12 Illustration of the system model perforation configurations considered: a) solid configuration, b) semi-perforated configuration, c) fully perforated configuration, and d) solid vertical wall section.

The SEAHIVE system model with the three perforation configurations and the two solid vertical sections were tested under 20 different water/wave conditions. Table 3 shows the water/wave conditions for this stage of the experiment (note: two water depths were considered: 0.50 and 0.70 m).

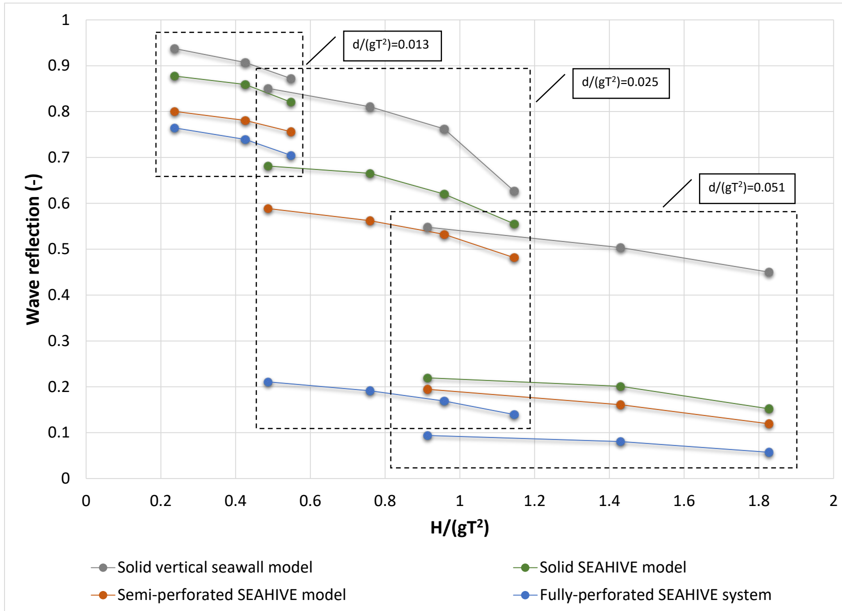
TABLE 3 Test conditions for Phase II testing on the vertical SEAHIVE system.

No	Frequency (Hz)	T (sec)	h (m)	H (m)
1	1.0	1.00	0.50; 0.70	0.10
2	1.0	1.00	0.50; 0.70	0.16
3	1.0	1.00	0.50; 0.70	0.20
4	0.7	1.43	0.50; 0.70	0.10
5	0.7	1.43	0.50; 0.70	0.16
6	0.7	1.43	0.50; 0.70	0.20
7	0.7	1.43	0.50; 0.70	0.24
8	0.5	2.00	0.50; 0.70	0.10
9	0.5	2.00	0.50; 0.70	0.16
10	0.5	2.00	0.50; 0.70	0.20

The performance of the system was characterized on the basis of water-level measurements taken using a combination of Ultrasonic Distance Meters and Wave Wires. Water-level measurements were found to include outliers and noise while being also affected by reflection. Therefore, the data analysis for this phase of the project started with the removal of outliers using interpolation based on adjacent values and filtering based on cutoff frequency ranges. Filtered water-level data was then analyzed according to short-term wave theory to calculate wave heights, with heights taken as the vertical distance between the maximum (wave crest) and minimum (wave trough) water level between two successive zero-up or down crossings. It should be noted that wave heights calculated following the aforementioned process are still biased by wave reflection from the "beach" located in the end of the SUSTAIN tank. Therefore, wave signals were further treated numerically following [6] to extract reflection. The resulting numerically separated signals were then explored to estimate wave reflection, wave transmission (for the fully perforated configuration only), as well as an estimate of the wave-energy dissipated.

Figure 13 shows the calculated wave reflection in front of the different perforation configurations of the SEAHIVE system model and the solid vertical wall section as a function of the wave steepness (H/gT^2) for the two water depths considered (0.50 and 0.70 m). Data series are clustered based on the relative water depth (d/gT^2), a key parameter for reflection estimations. Wave reflection is found to decrease as wave steepness and relative water depth increase. The comparison of the reflection between the solid SEAHIVE system with the solid vertical wall section reveals that the hexagonal faceted geometry and the stepped configuration of the SEAHIVE system model decreases wave reflection with the exact amount depending on the condition. Perforations are found to further decrease reflection with the differences varying from approximately 15 to 70% depending on the configuration and the water/wave conditions.

Figure 14 shows the wave energy dissipated for the different perforation configurations of the SEAHIVE system model and the solid vertical wall sections. The wave energy dissipated was determined by subtracting the total incident wave energy from the reflected and transmitted energy estimates. Similar to wave reflection, the relative water depth (d/gT^2) has a dominant effect on the results. The faceted geometry and the stepped configuration of the SEAHIVE system model combined with the effect of perforations promotes wave-energy dissipation with the exact value depending on the configuration and the water/wave conditions. However, the effect is not substantial in all the wave conditions. Overall, the SEAHIVE system dissipates 1.2 to 3.5 times more energy compared to a traditional solid vertical seawall.



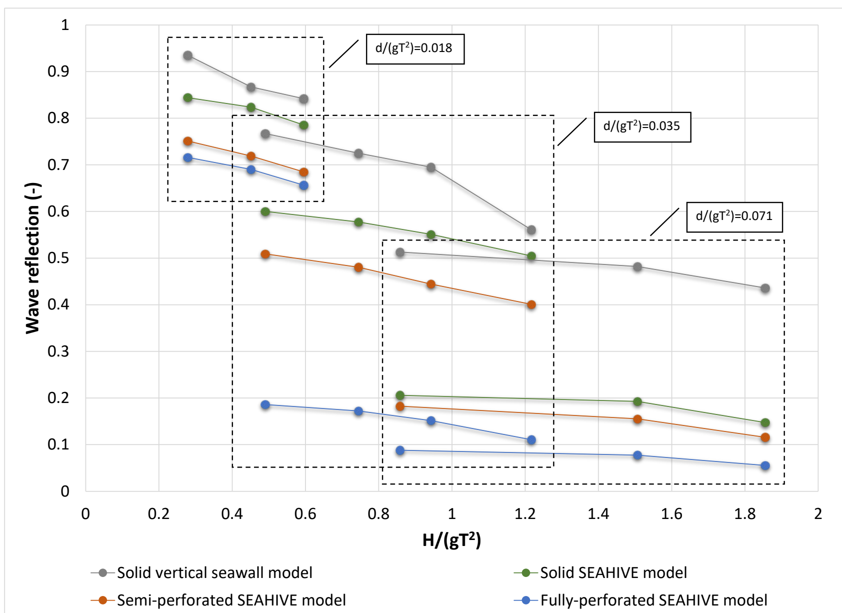


FIGURE 13 Wave reflection for the different perforation configurations of the SEAHIVE system model and the solid vertical wall sections (top: water depth of 0.50m; bottom: water depth of 0.70m).

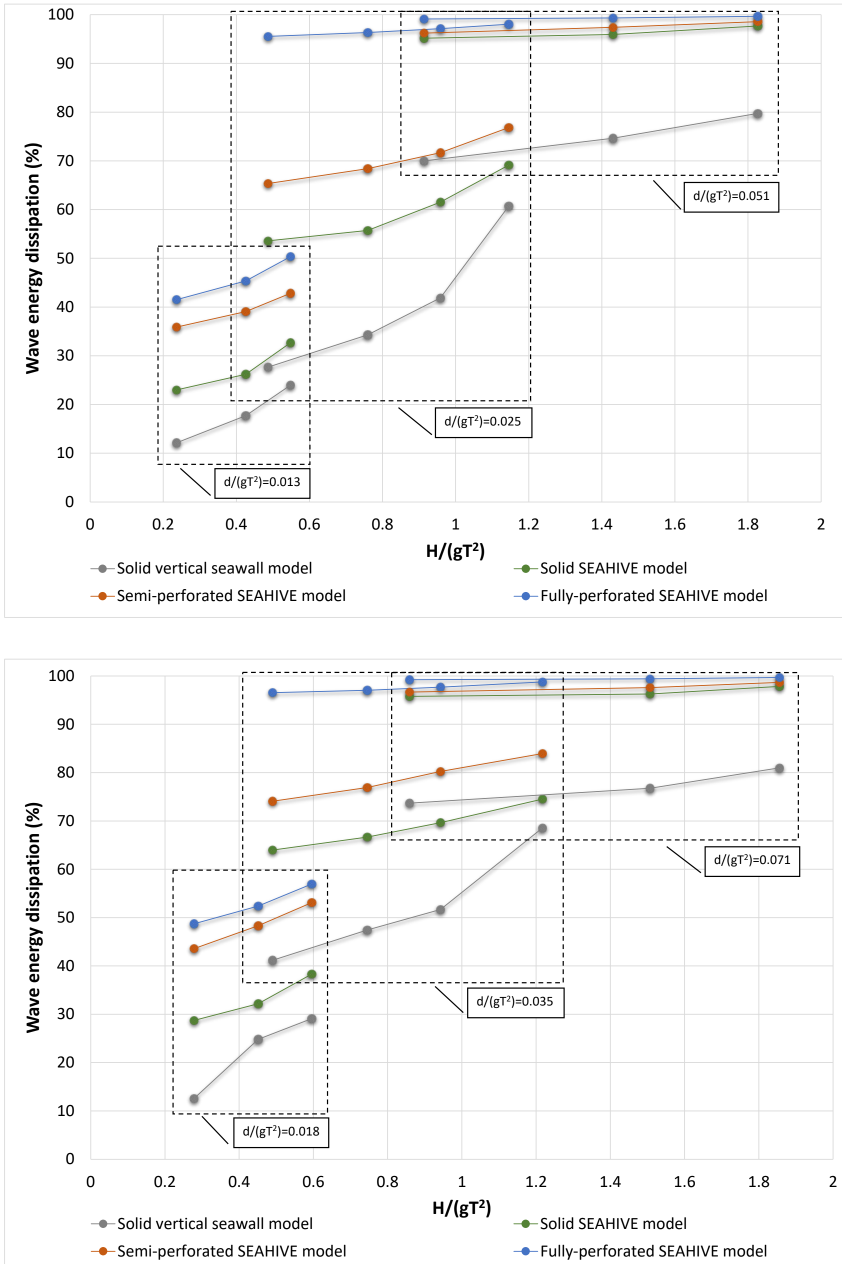


FIGURE 14 Wave energy dissipated for the different perforation configurations of the SEAHIVE system model and the solid vertical wall sections (top: water depth of 0.50m; bottom: water depth of 0.70m).

Motivated by the interests of other researchers and local stakeholders on applications, such as rip rap and hybrid reefs, additional tests were conducted on a horizontal SEAHIVE system. It should be noted that the system configurations considered being based on the horizontal stacking of multiple SEAHIVE elements required a change in the scale of the experimental study and consequently a re-evaluation of the water/wave conditions. A new model was thus constructed out of wood hollow perforated hexagonal prismatic elements with a circumscribed theoretical diameter of 0.28 m (hexagonal side length of 0.14 m) and a length of approximately 1.20 m (geometric scale of 1:10). For the submerged reef application, the model was composed of three-unit elements with two elements at the base and one on the top. The model was tested in a solid and perforated configuration while the results were compared with a trapezoidal reef module of the same height that was used as reference. Although perforations were smaller in size, the perforated configuration of the model had the same ratio of void wall surface over solid wall surface with the previous experiments. Figure 15 illustrates the two horizontal SEAHIVE configurations considered and the trapezoidal reef of reference, while Figure 16 shows the model in the SUSTAIN tank. Similar to the vertical model testing, the performance of the system was evaluated on the basis of water-level measurements before and after the models for a series of water/wave conditions defined through a similarity study. Table 4 shows the water/wave conditions considered for this part of the study.

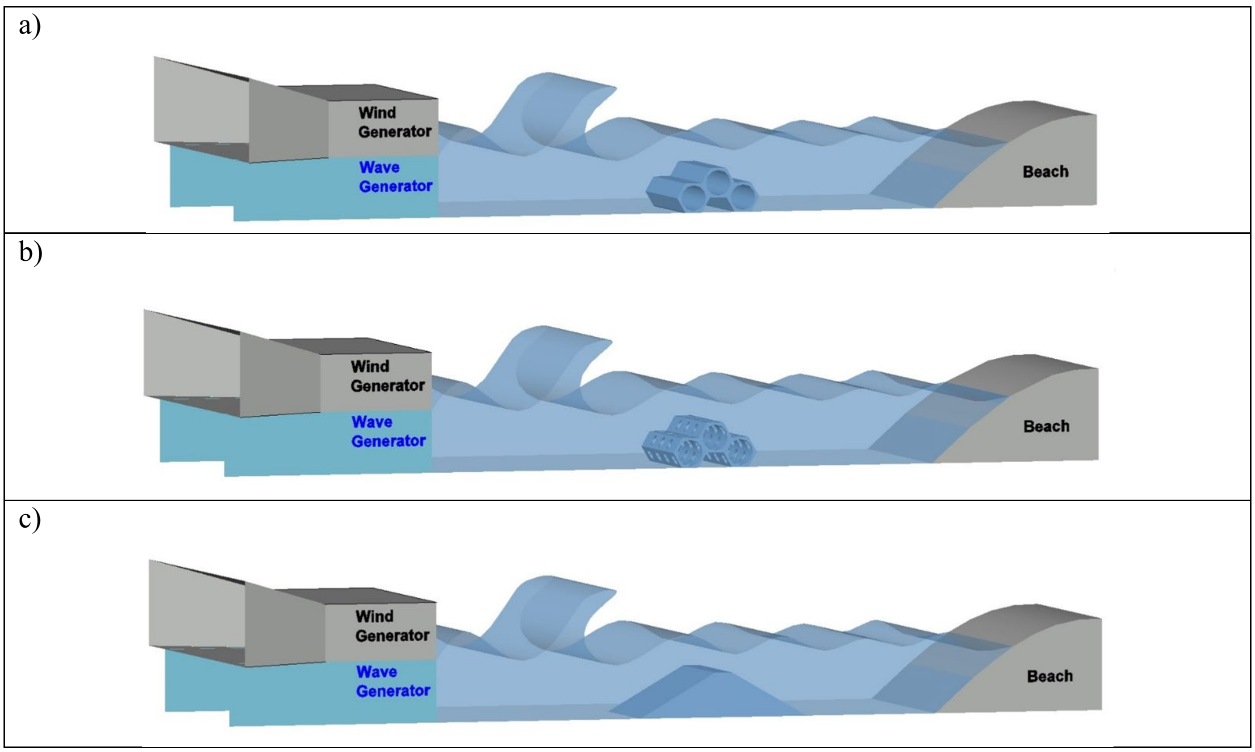


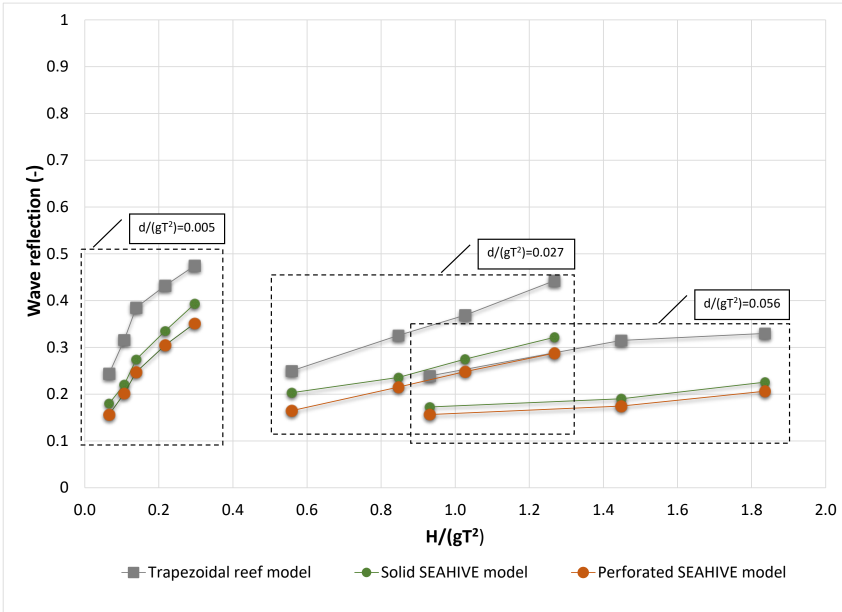
FIGURE 15 Illustration of the two submerged horizontal SEAHIVE configurations considered a) solid and b) perforated along with c) the trapezoidal reef model of reference.

FIGURE 16 Submerged horizontal SEAHIVE system model configurations in SUSTAIN.

TABLE 4 Test conditions for the horizontal SEAHIVE system testing.

No	Frequency (Hz)	T (sec)	h (m)	H (m)
1	1.0	1.00	0.55; 0.75	0.10
2	1.0	1.00	0.55; 0.75	0.16
3	1.0	1.00	0.55; 0.75	0.20
4	0.7	1.43	0.55; 0.75	0.10
5	0.7	1.43	0.55; 0.75	0.16
6	0.7	1.43	0.55; 0.75	0.20
7	0.7	1.43	0.55; 0.75	0.24
8	0.3	3.33	0.55; 0.75	0.10
9	0.3	3.33	0.55; 0.75	0.16
10	0.3	3.33	0.55; 0.75	0.20
11	0.3	3.33	0.55; 0.75	0.24
12	0.3	3.33	0.55; 0.75	0.30

Figures 17 and 18 show the wave reflection and transmission for the horizontal SEAHIVE system configurations and the trapezoidal reef of reference, while Figure 19 shows the wave energy dissipation. All three are shown as a function of the wave steepness (H/gT^2) with data series clustered also based on the relative water depth (d/gT^2). One can observe that as the relative water depth decreases there is more interaction with the models. The submerged horizontal configurations present wave overtopping, and thus higher transmission rate and less dissipation. The analysis of the data revealed that wave height plays an important role on the performance of the models with wave reflection and wave energy dissipation (from wave breaking and friction) increasing when the wave height increases, while wave transmission decreases. Overall, the horizontal SEAHIVE system was found to have less reflection but similar wave-energy dissipation with the trapezoidal reef model. Perforations were found not to have an impact in the performance of the system. However, since perforation size was not a parameter in this experiment, it is believed that this result reflects a design effect rather than a generalized trend.



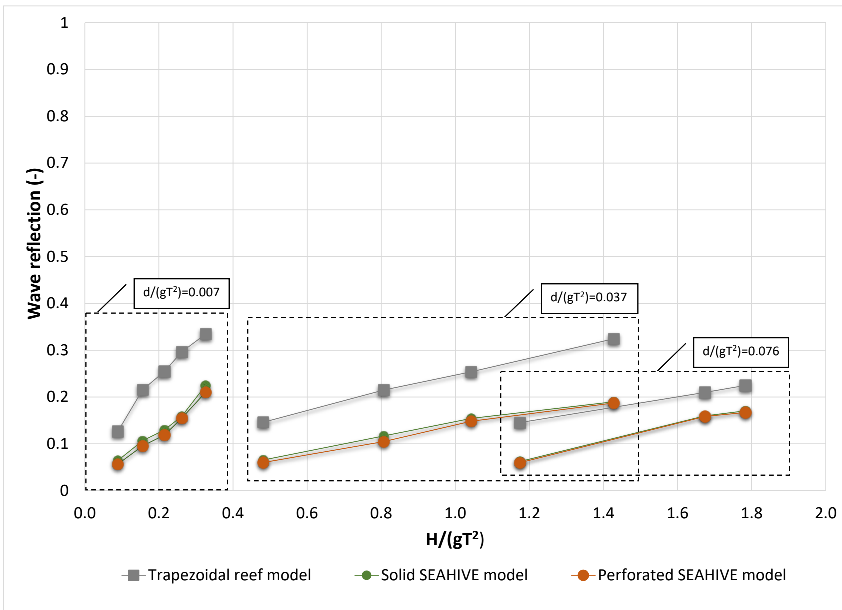


FIGURE 17 Wave reflection for the horizontal SEAHIVE model configurations and the trapezoidal reef model (top: water depth of 0.55m; bottom: water depth of 0.75m).

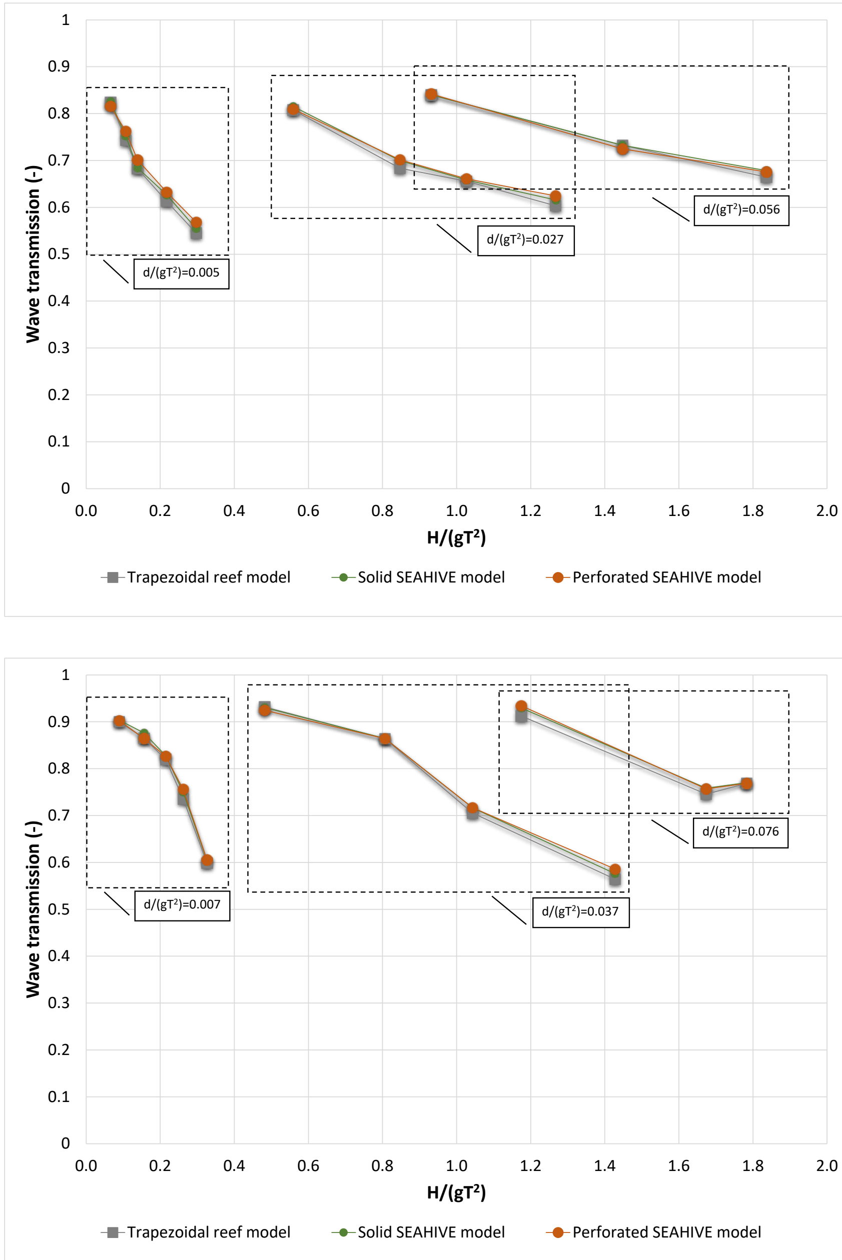
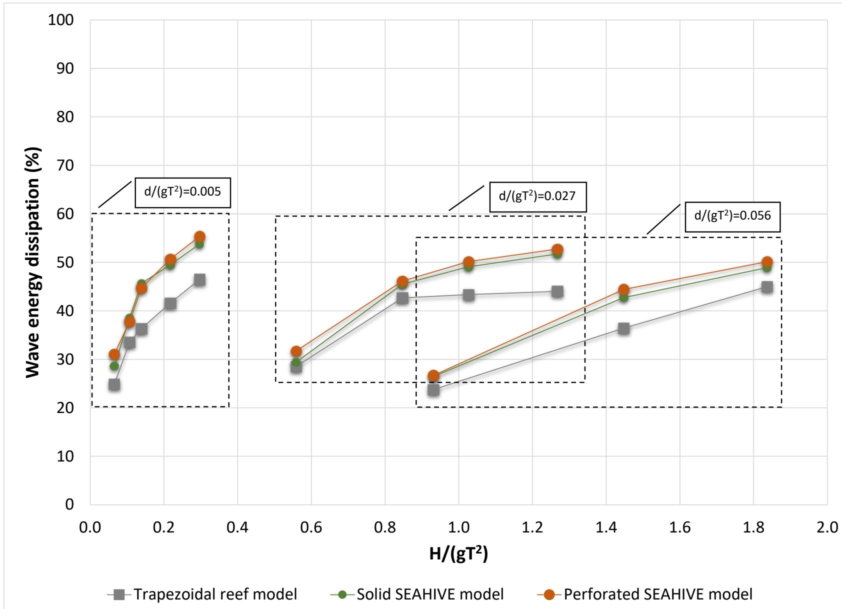


FIGURE 18 Wave transmission for the horizontal SEAHIVE model configurations and the trapezoidal reef model (top: water depth of 0.55m; bottom: water depth of 0.75m).



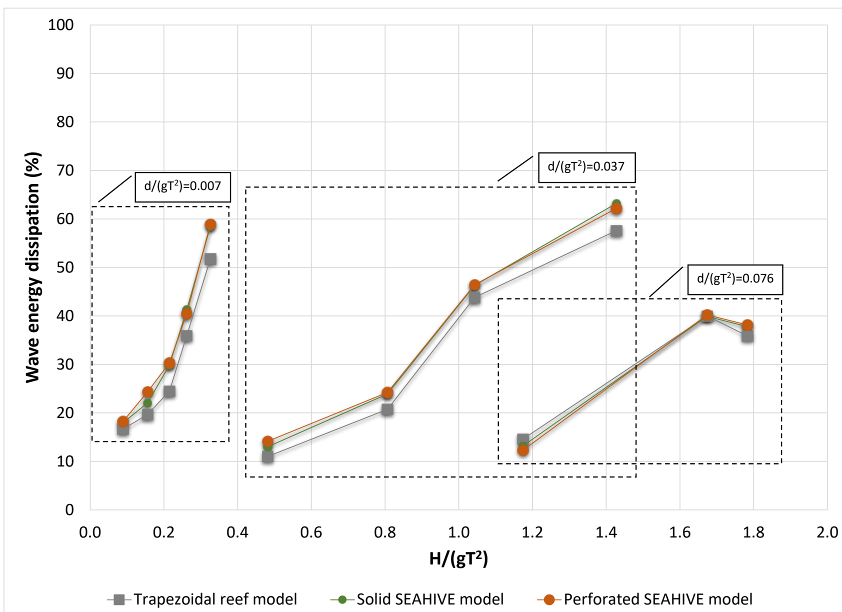


FIGURE 19 Wave energy dissipated for the horizontal SEAHIVE model configurations and the trapezoidal reef model (top: water depth of 0.55m; bottom: water depth of 0.75m).

PLANS FOR IMPLEMENTATION

With respect to implementation of the project, the SEAHIVE project was showcased into a series of presentations and conference including the 2019 Florida Shore & Beach Preservation Association (FSBPA) Annual Conference and the 2019 Coastal Structures, an international conference organized by the American Society of Civil Engineering's (ASCE) Coasts, Oceans, Ports, and Rivers Institute (COPRI). The system was also discussed in meetings with local stakeholders, professionals and government officials including North Bay Village, the City of Miami Beach, the City of Pompano Beach, Miami-Dade County, the Florida Fish and Wildlife Conservation Commission (FWC), as well as the Florida North and East Central Estuarine Restoration Teams (NERT and ECERT, respectively). All these organizations are part of the SEAHIVE targeted audience. In addition, the work included in this report will also be the focus of two upcoming journal publications. The project also featured in several public communications such as the 2021 NBC6 First Alert Weather Hurricane Special and in Weather Underground by the Weather Channel receiving thus both local and national coverage (Figure 20). Through these efforts and with the help of the expert panel members, the PIs secured three pilot installations for the SEAHIVE project in collaboration with local communities including a revetment application in North Bay Village, Florida, a hybrid coral reef design offshore of Miami Beach, Florida, and a seawall/mangrove planter concept in Pompano Beach, Florida. The PIs developed the related SEAHIVE designs considering each project's needs and site conditions while also assisting project owners with permitting and construction aspects. It should be noted that while these installations provide a unique opportunity for testing the SEAHIVE product in its operational environment, they were not included in the initial proposal and budget.

FIGURE 20 Snapshot from 2021 NBC6 First Alert Weather Hurricane Special SEAHIVE segment.

For the revetment application in North Bay Village, Florida, the PIs have been coordinating with Village officials and the homeowner's association of Treasures in the Bay to design, to produce and install six SEAHIVE units as a green engineering riprap alternative in front of a newly constructed seawall (Figure 21). The units represent 1.2-meter-long concrete perforated hexagonal tubes with a theoretical diameter of 0.6 m and a series of perforations on their side faces that will provide passage for water flow under surging or breaking waves dissipating the wave energy within the elements while adding structural complexity to the system. Structural complexity combined with the use of concrete with non-corrosive reinforcement is expected to increase the potential of the system for biocompatibility. Both the ecological and engineering performance of the system will be monitored after installation. The project is currently under permit review by the Miami-Dade Department of Environmental Resources Management (DERM) with the PIs addressing during this quarter the comments provided on the original permit application.

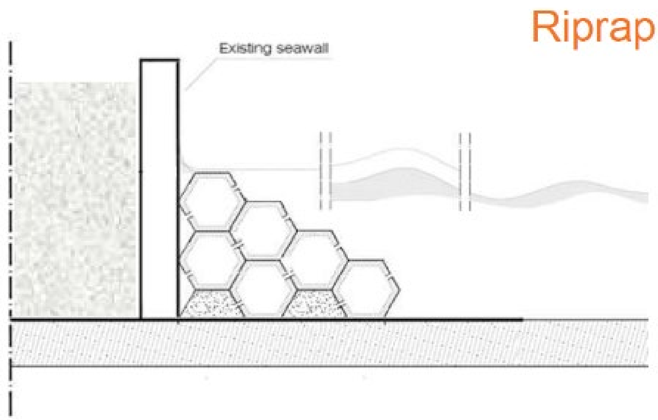


FIGURE 21 Illustration of the SEAHIVE riprap pilot installation in North Bay Village, FL.

For the hybrid coral reef application, the PIs have been working with the City of Miami Beach and other UM researchers in the context of a University of Miami (UM) Laboratory for INtegrative Knowledge (U-LINK) project that investigates hybrid coral reefs for shoreline protection. The project includes the installation of three 5.5 m long prototype structures, including a SEAHIVE one (Figure 22), that will be populated with corals from the UM nurseries and monitored to quantify their impact on wave action. For this installation, the PIs designed a SEAHIVE reef structure (incl. sizing and stability analysis) and assisted the City's Environment & Sustainability Department in acquiring the required permits by the U.S. Army Corps of Engineers, Miami-Dade Department of Environmental Resources Management (DERM) and the Florida Department of Environmental Protection (FDEP). All permits required for this pilot installation have been issued, and the manufacturing of the SEAHIVE units is in progress with the installation of the SEAHIVE reef structure scheduled for April 2022. It should be noted that the SEAHIVE reef structure and the other structures will be instrumented and monitored by United States Geological Survey (USGS) experts who are interested in the performance of hybrid artificial coral reefs.

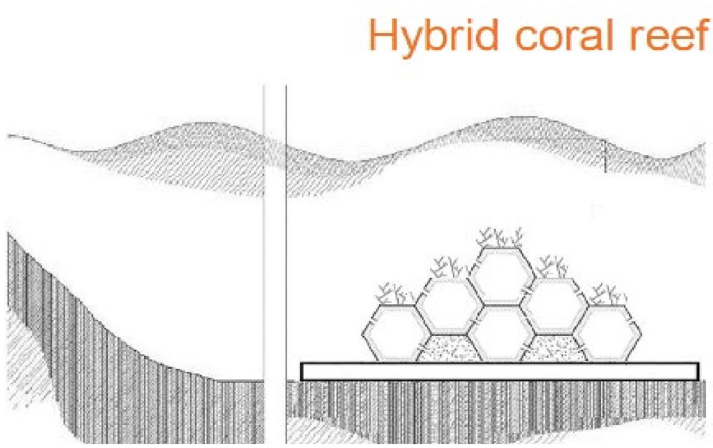


FIGURE 22 Illustration of the SEAHIVE coral reef installation offshore of Miami Beach, FL.

The third installation secured by the PIs will take place in the shallow protected waters of Hillsboro Inlet Park in Pompano Beach, Florida, where an educational marine park named Wahoo Bay is under development. The park is the product of a collaboration between Shipwreck Park (a non-profit organization), the City of Pompano Beach, Broward County and the University of Miami. For this installation, the PIs worked with the stakeholder team to propose a SEAHIVE system designed to protect as well as to provide habitat through halophyte vegetation transplanting (e.g. mangroves, salt marshes) and an integrated artificial reef. The system is made of six 6 m long sections composed of 12 SEAHIVE elements with a theoretical diameter of 0.9 m (Figures 23-24). Wahoo Bay has been fully permitted as of January 25, 2022; the manufacturing of the SEAHIVE units is thus in progress with the installation of the SEAHIVE system scheduled for later this spring. It should be noted that FWC is funding 1/3 of the cost of fabrication of the SEAHIVE system ($50,000), while the University of Miami (UM) Laboratory for INtegrative Knowledge (U-LINK) is supporting an interdisciplinary team of experts ($100,000) to monitor the deployment and performance of the system.

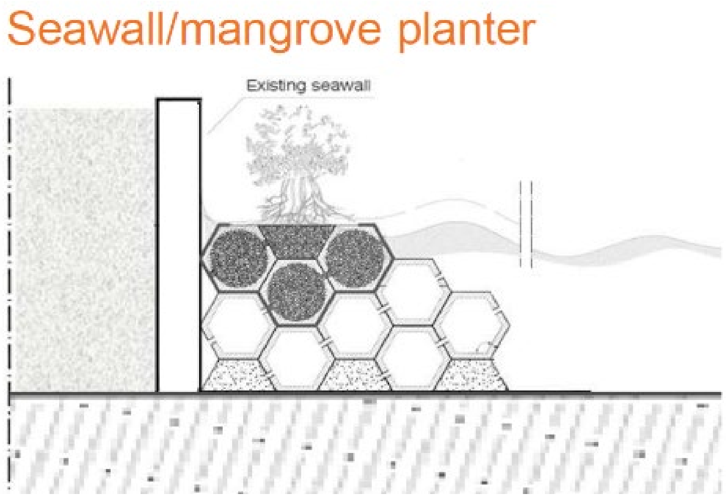


FIGURE 23 Illustration of the Wahoo Bay SEAHIVE system to be installed in Pompano Beach, FL.

FIGURE 24 Rendering of the Wahoo Bay Park in Pompano Beach, FL. Credit: Gallo Herbert Architects

CONCLUSIONS

The SEAHIVE IDEA project focused on the research and development of a novel engineered marine and estuarine protection system that dissipates wave energy and creates habitat by providing passage to water. Perforations on the side faces of SEAHIVE elements provide passage for water flow under surging or breaking waves dissipating the wave energy within the system while adding also structural complexity to the structure and thus improving its potential for biocompatibility and habitat creation. Traditional solutions, such as seawalls or breakwaters, utilized to improve community safety in the face of high-intensity storms and flooding, are typically designed to reflect back wave energy and do not provide a hospitable environment for biodiversity.

The system's investigation was conducted on the basis of physical tests at the University of Miami SUrge STructure Atmosphere INteraction (SUSTAIN) Facility and morphological considerations. During Phase I, a morphological investigation on the cross-sectional profiles for the elements composing the system was conducted considering geometrical properties as well as other aspects such as element manufacturing with SEAHIVE prototype elements tested individually at the SUSTAIN Facility under different water/waves conditions defined through a dimensional analysis of the Froude number. Obtaining reliable wave-induced pressure measurements was however found to be very challenging; the experimentally defined envelope pressure profiles vary thus significantly between prototype elements with different cross-sectional profiles, the void configuration and the water/wave conditions. It is thus advised to focus on other measurements. Therefore, Phase II system-design testing focused on the hydrodynamic performance of the SEAHIVE with the testing of a vertical SEAHIVE wall section in the SUSTAIN wind/wave tank. For this phase of the testing, the analysis was conducted on the basis of the water-level measurements as they allow to characterize the performance of the system through estimates of wave reflection and wave-energy dissipation. The comparison of the reflection coefficient between the vertical SEAHIVE system model with a solid vertical wall model revealed that the SEAHIVE system model decreases significantly wave reflection while also dissipating more energy. Tests conducted on horizontal SEAHIVE system configurations revealed that the system performs also well in other contexts from riprap to submerged breakwater/reef applications. These experimental results combined with the versatility and great potential of the system for habitat creation identify it as an advantageous solution for the protection of the built environment and the transportation network in the coastal areas with its implementation path including three pilot installations in South Florida in collaboration with local municipalities. All installations are underway and will be monitored to assess the ecological and engineering performance of the system, as well as to acquire important techno-economic data for further developments, as well as for deployment of the product to the practice. Finally, future work may focus on the hydrodynamic and structural optimization of the system as well as material durability studies.

INVESTIGATORS' PROFILES

- **Landolf Rhode-Barbarigos (Principal Investigator)**

Dr. Rhode-Barbarigos is an Assistant Professor in the Department of Civil and Architectural Engineering at the University of Miami. He specializes in structural morphology, design and analysis of structures, with specific interest in form finding and optimization.

- **Brian Haus (Key Investigator)**

Dr. Haus is Chair and Professor of Ocean Sciences at the Rosenstiel School of Marine and Atmospheric Science of the University of Miami and Director of the Surge-Structure-Atmosphere-INteraction (SUSTAIN) Facility. He is an expert in hurricane-force winds and waves and their impacts on coastal structures.

- **Antonio Nanni (Key Investigator)**

Dr. Nanni is Chair and Professor of Civil and Architectural Engineering at the University of Miami. He specializes in structural materials and design, with specific interest in construction materials, their structural performance and field application.

- **Mohammad Ghiasian (Graduate Research Assistant)**

Dr. Mohammad Ghiasian was a PhD student in the Department of Civil and Architectural Engineering at the University of Miami. His research focused on the morphogenesis of efficient and ecofriendly coastal structures, as well as the role of green infrastructure such as coral reefs on storm surge and waves.

- **Prannoy Suraneni (Collaborator)**

Dr. Suraneni is an Assistant Professor in the Department of Civil and Architectural Engineering at the University of Miami. He is an expert in the materials science, chemistry, and engineering of cementitious materials.

- **Esber Andiroglu (Collaborator)**

Dr. Andiroglu is an Associate Professor of Practice in the Department of Civil and Architectural Engineering at the University of Miami and Chair of the Master's Program in Construction Management. He specializes in sustainable design and construction.

- **Rafael Araujo (Collaborator)**

Dr. Araujo is a Senior Research Associate at the Department of Marine Biology and Ecology at the Rosenstiel School of Marine and Atmospheric Science of the University of Miami. He is an expert in mangrove ecology and conservation.

- **Diego Lirman (Collaborator)**

Dr. Lirman is an Associate Professor at the Department of Marine Biology and Ecology at the Rosenstiel School of Marine and Atmospheric Science of the University of Miami. He specializes in coastal ecology and conservation.

- **Andrew Baker (Collaborator)**

Dr. Baker is a Professor at the Department of Marine Biology and Ecology at the Rosenstiel School of Marine and Atmospheric Science of the University of Miami. He is an expert in coral ecology, biology, and conservation.

- **Kathleen Sullivan Sealey (Collaborator)**

Dr. Sealey is a Professor of Biology at the University of Miami. Her research seeks to build collaborative, problem-based inquiry addressing complex challenges facing society while maintaining ecological functionality.

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APPENDIX RESEARCH RESULTS

Sidebar Info

Program Steering Committee: NCHRP IDEA Program Committee
Month and Year: April 2022
Title: SEAHIVE - Sustainable Estuarine and Marine Revetment
Project Number: NCHRP IDEA-213
Start Date: October 24, 2018
Completion Date: April 30, 2022
Product Category**:** Coastal Highway Infrastructure Safety and Protection
Principal Investigator: Landolf Rhode-Barbarigos, Dr.
E-Mail: landolfrb@miami.edu
Phone: 305-284-3489

TITLE:
SEAHIVE - Sustainable Estuarine and Marine Revetment

SUBHEAD:
Test-driven design of an efficient and sustainable modular shoreline protection system that dissipates wave energy and promotes habitat creation

WHAT WAS THE NEED?
Storm surge and wave action induce destructive forces to coastal communities that can result in loss of life, shoreline erosion, as well as structural damages to the built environment and infrastructure including the transportation network. Traditional shoreline protection structures, such as seawalls, do not dissipate wave energy while compromising habitat and reducing biodiversity. On the other hand, living shorelines are not generally applicable in areas with small footprint availability and/or harsh wave conditions and high storm surges. Therefore, it is crucial to investigate more efficient and sustainable shoreline protection systems against waves and storm-surges.

WHAT WAS OUR GOAL?
The objective of this project has been the research and development of a sustainable estuarine and marine revetment system that dissipates wave energy and promotes habitat creation.

WHAT DID WE DO?
A novel engineered marine and estuarine protection system, named SEAHIVE after its hexagonal geometry, that dissipates wave energy and creates habitat was investigated through physical testing at the University of Miami SUrge STructure Atmosphere INteraction (SUSTAIN) Facility, a wind/wave tank with unique capabilities. Moreover, with the help of the expert panel members, three SEAHIVE pilot installations were secured in South Florida collaboration with local communities (City of Miami Beach, City of North Bay Village, City of Pompano Beach, Miami-Dade County, and Broward County) and organizations (University of Miami, FDOT, Shipwreck Park Foundation, Florida Fish and Wildlife Conservation Committee). The pilot installations, which are currently under way, will be monitored to assess the ecological and engineering performance of the system under real conditions, as

well as to acquire important techno-economic data for further developments as well as for deployment of the product to the practice.

WHAT WAS THE OUTCOME?

The outcome of this project is SEAHIVE, a novel engineered marine and estuarine protection system that dissipates wave energy and promotes habitat creation. The laboratory testing on SEAHIVE models showed that the complex facetted geometry of the proposed system reduces wave reflection while perforations decrease it even further with the exact values depending on the water level and the wave characteristics. The facetted stepped model with progressively varying porosity was found to dissipate also significantly more energy compared with its solid version and the solid vertical seawall model with perforations on the side faces of the elements forming interconnected channels that allow flow of water under surging or breaking waves and thus wave energy dissipation through turbulence inside the system. The SEAHIVE system provides thus better protection against storm surge and wave action than traditional coastal protection structures. The engineering and ecological performance of the system will be tested under real conditions in the pilot installations that are currently under way in collaboration with local communities.

WHAT IS THE BENEFIT?

Physical testing on SEAHIVE system revealed the system provides better protection against storm surge and wave action than traditional coastal protection structures such as vertical seawalls and trapezoidal submerged breakwaters. Moreover, the complex geometry of the system combined with the use of ecofriendly materials is expected to also increase the system's biocompatibility and potential for habitat creation. It should be noted that SEAHIVE elements are being manufactured using traditional concrete pipe casting techniques and utilizing biophilic concrete mixtures and non-corrosive reinforcements minimizing thus environmental impacts and extending service life. Considering the adaptive features for various applications and topography, as well as its potential for habitat creation, the SEAHIVE system provides an efficient and cost-effective eco-engineering alternative for the protection of the transportation network and the built environment in coastal communities that can be tuned for both low and high energy areas. With the cost of coastal protection in the United States projected to skyrocket to $400 billion by 2040 according to the Center for Climate Integrity, the proposed system presents a great payoff potential.

LEARN MORE

For detail, please refer to the Project NCHRP-213 final report on the NCHRP IDEA Program website.