Conference Paper, Published Version

Ghiasian, Mohammad; Rossini, Marco; Amendolara, Joel; Haus, Brian; Nolan, Steven; Nanni, Antonio; Bel Had Ali, Nizar; Rhode-Barbarigos, Landolf

Test-Driven Design of an Efficient and Sustainable Seawall Structure

Coastal Structures 2019 - Nils Goseberg, Torsten Schlurmann (eds) - © 2019 Bundesanstalt für Wasserbau
ISBN 978-3-939230-64-9 (Online) - DOI: 10.18451/978-3-939230-64-9_122

Test-Driven Design of an Efficient and Sustainable Seawall Structure

M. Ghiasian & M. Rossini
Dept. of Civil, Architectural and Environmental Engineering, College of Engineering, University of Miami, Coral Gables FL, USA

J. Amendolara & B. K. Haus
Dept. of Ocean Sciences, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami FL, USA

S. Nolan
State Structures Design Office, Florida Department of Transportation, Tallahassee FL, USA

A. Nanni
Dept. of Civil, Architectural and Environmental Engineering, College of Engineering, University of Miami, Coral Gables FL, USA

N. Bel Had Ali
Ecole Nationale d'Ingénieurs de Gabès, University of Gabès, Gabès, Tunisia

L. Rhode-Barbarigos
Dept. of Civil, Architectural and Environmental Engineering, College of Engineering, University of Miami, Coral Gables FL, USA

Abstract: Seawalls are among the most widely applied and reliable options for reducing wave action and the impact of storm surge in coastal regions susceptible to damages from windstorms and coastal flooding events. However, existing seawall designs often do not provide the desired level of protection especially under high tidal flow, additionally in many cases they negatively impact the local shoreline ecosystem. This paper focuses on the development of a novel seawall system, called SEAHIVE. The system, composed of a series of perforated tubular elements, is designed to allow wave-energy to dissipate within the elements increasing material efficiency and performance. Moreover, SEAHIVE elements are made of low alkalinity cement with seawater and non-corrosive reinforcement rebars avoiding corrosion and promoting sustainability. The SEAHIVE design development is conducted based on measurements from physical testing at the Surge Structure Atmospheric Interaction (SUSTAIN) Facility at the University of Miami and auxiliary biocompatibility studies related to material composition and structural complexity. This process can enhance the design of the system thereby opening the door to the development of a whole new realm of shoreline protection structures with increased efficiency and enhanced biocompatibility features.

Keywords: Shoreline protection, seawall, design, biocompatibility, wave, wind, hurricane, experimental testing, biocompatibility.

1. Introduction

As the recent impacts of hurricanes Irma, Maria and Michael revealed, coastal regions are always susceptible to weather and climate disasters from severe storms, tropical cyclones and flooding. Considering that average annual temperatures and sea level will continue to rise making extreme events more damaging, it is critical to investigate novel design solutions for shoreline protection that protect coastal structures without damaging the environment.

Shoreline protection includes systems that span from softer "green" solutions, such as living shorelines, to hardened "gray" designs (coastal armoring), such as seawalls. Living shorelines are often considered as the ideal barrier (Gittman et al. 2016), but their protectiveness is often not adequate for conditions with high-energy tidal flow, watercraft wake or wave attack (CEM, 2008). Revetments are often considered as a compromise between nature-based alternatives and armoring

(SPM, 1973). In revetments, the rocks employed must be strong, heavy and durable for strong waves and therefore granite is typically employed. However, accessibility to appropriate natural materials may become challenging in the future. Moreover, revetments typically do not provide a hospitable environment for biodiversity nor do they possess regenerative features after storm-wave attack. For shores with large waves, long fetch and/or a steep slope, seawalls are typically employed as the most applicable and reliable solution (Gilbert and Velinga 1990). However, in many cases existing seawall designs come with relatively high construction and maintenance costs according to the study of the Governor's South Atlantic Alliance (2017). In addition, typical seawalls can cause considerable negative effects on coastal ecosystems. Seawalls typically support 23% lower biodiversity and 45% fewer organisms than riprap and natural shorelines (Gittman et al. 2015). Therefore, this paper focuses on the development of a novel efficient and ecofriendly seawall system, called SEAHIVE, through experimental testing in the SUrge STructure Atmosphere Interaction (SUSTAIN) Facility and auxiliary biocompatibility tests.

2. Design considerations on wave-breaking and wind action

According to structural design guidelines and standards, such as ASCE 7 (2016) and the Coastal Engineering Manual (2008), shoreline protection structures are designed considering flood, wind and earthquake action, while their performance is evaluated in terms of surface wave transmission, reflection properties, energy dissipation characteristics, and shoreline response such as sediment transport rates. Biocompatibly may be considered as a secondary criterion for evaluation. In the design of coastal structures, wind action must be considered in combination with wave and flood effects. Wave breaking forces are often the most critical design load for shoreline protection structures. Following ASCE 7 (2016), wave-breaking forces must be included in the design of structures in both V-Zone (an area within a special flood hazard area, extending from offshore to the inland limit of an open coast) and A-Zone (an area within special flood hazard area, landward of a V-Zone or landward of an open coast). The wave-breaking force per unit length on a vertical wall assuming that the space behind the vertical wall is dry is given by Eq. (1):

$$F_{brkw} = 1.1 C_p \gamma_w {d_s}^2 + 2.4 \gamma_w {d_s}^2 \quad (1)$$

where C_p is the dynamic pressure coefficient related to risk category of a building, γ_w is the specific weight of water and d_s is the design still water depth. Eq. (1) follows the Homma and Horikawa (1964-1965) model that assumes a reflected wave in front of the vertical wall with the crest of $1.2d_s$ above the design still water level and takes into consideration both static and dynamic effects from wave breaking on a vertical wall (Fig. 1).

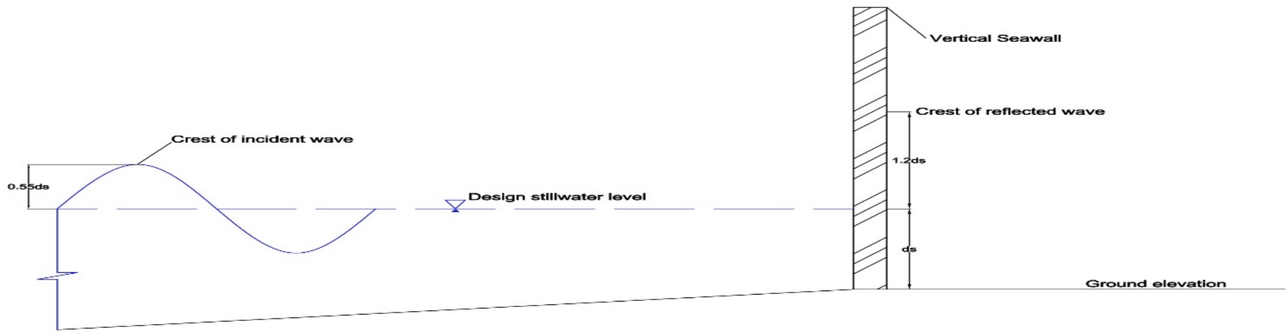

Fig. 1. Incident wave breaking against a vertical wall.

In the design of coastal structures, wind action must be considered in combination with flood effects. Following ASCE 7 (2016) wind loads can be determined through three different methods: directional, envelope and wind tunnel testing. Wind tunnel testing is required for special cases with complex geometries. In regular cases, the directional and the envelope method can be employed to define the wind loading with great accuracy (FEMA P-55, 2011). Wind pressures on each surface of a structure are calculated based on the wind maps of region where the structure is located, structural system, exposure category, risk category, and the importance of the structure as well as its use.

The design and performance evaluation of shoreline protection structures in hurricane-prone areas should be conducted the action of flooding which can occur from runoff due to heavy rainfall or storm surge sources. Therefore, design guidelines and standards, such as ASCE 7 (2016), include load combinations for structures located in a special flood hazard area with flood loads factored by 1.5 and 2.0 when added to other loads in the Allowable Strength Design (ASD) and the Load and Resistance Factor Design (LRFD) methods, respectively. However, it should be noted that the three hazard components wave, wind and flooding are not independent. Modeling the interaction between waves and winds during windstorms and coastal flooding events is a challenging process. The airflow is known to separate from the surface as the wave breaks, which in intense winds can lead to a detached airflow over much of the wave form and a reduction in the aerodynamic drag coefficient (Donelan et al. 2004). Large sea-spray particles (spume) generated during the wave breaking process in extreme winds may also play an important role in the air-sea coupling (Soloviev et al. 2014) and in impacts on structures. Flood levels can alter the wave impacts by reducing or enhancing local wave breaking. Consequently, existing load combinations may not properly reflect the wave/wind interaction under hurricane requiring further investigation.

3. Test-based design of the SEAHIVE seawall system

Although the effects of wave and wind action on the built environment have been topics of on-going investigations for decades, models for defining their combined effect on shoreline protection structures, assessing their performance and biocompatibility are still lacking. Therefore, the design of the proposed novel seawall system is developed through a series of experimental tests defined in SUrge STructure Atmosphere Interaction (SUSTAIN) Facility (Fig. 2) at the University of Miami and auxiliary biocompatibility tests. SUSTAIN has the unique capability of generating winds up to category 5 strength on the Saffir-Simpson scale combined with mechanically generated waves of variable frequency, wavelength, direction and amplitude. Variable storm surge/flooding ranges can also be tested by varying the water level relative to the test specimen and by producing very low frequency oscillations in the test basin to drive currents of up to ~0.3 m/s. These capabilities are exploited to study the loads on the proposed seawall system, through testing the same wind-wave-surge conditions at multiple physical model scales.

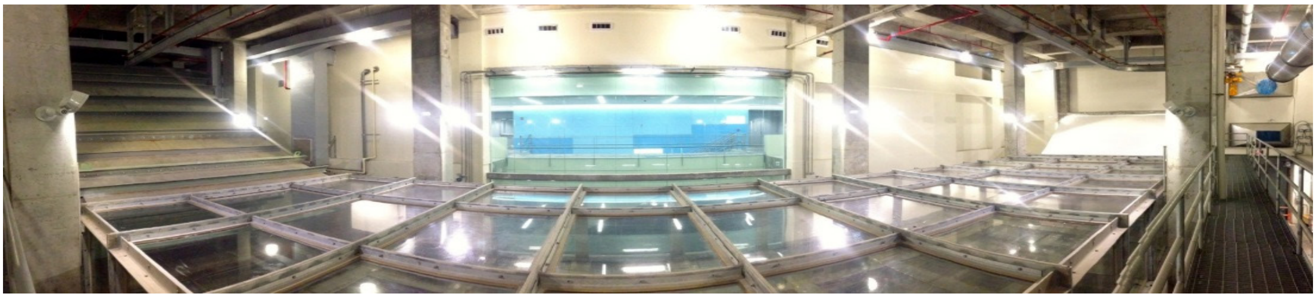

Fig. 2. Panoramic photo of the University of Miami, Surge STructure Atmospheric Interaction (SUSTAIN) tank.

The proposed seawall system is called SEAHIVE. It is composed of series of perforated hollow tube elements with circular, hexagonal and square cross-sections being investigated (Fig. 3). Perforations on the side faces of the elements provide passage for water flow under surging or breaking waves dissipating the wave energy within the elements. In a system configuration, the perforations can form interconnected channels providing habitat and protection for marine life. Ecological engineering studies (Bergen et al. 2001) have shown that adding structural complexity to the designs of protective systems improves their biocompatibility (Chapman and Blockley, 2009). Biocompatibility is also promoted through material selection. SEAHIVE will be manufactured using fiber-reinforced low alkalinity concrete with non-corrosive rebars. The low alkalinity feature with reduced use of Portland cement and no chloride limits (sea-concrete) concrete combined with the use of non-corrosive reinforcing (GFRP, BFRP or CFRP) for deep stacked installations or high wave energy impact further improves compatibility with marine life and sustainability.

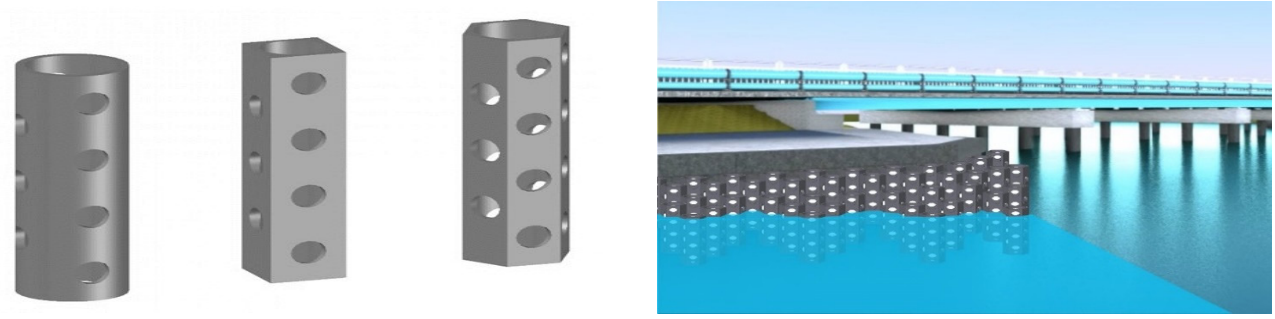

Fig. 3. Illustrations of SEAHIVE element units (left) and of a vertical system application (right).

The modularity of the SEAHIVE system has adaptive features allowing elements to be oriented vertically or horizontally paving the way for various applications and topographies. In addition, the system can be employed as an independent shore protection system or an auxiliary system enhancing existing shore protection structures. The voids in the elements can be filled with granular material for application in high-energy locations or left open for maximum flushing and dissipation effects. Elements at higher elevations can be filled with sand and soil to promote coastal vegetation. As a result, the system can be adapted to generate a desired slope and dissipation capacity. Due to the high structure complexity of SEAHIVE elements, the system is also expected to have low reflection and tunable wave transmission, while dissipating bottom flows at the toe of structure that can lead to a stable situation to prevent scouring.

In absence of universally accepted guidelines for defining the combined wave/wind loads and evaluating the performance and biocompatibility of the proposed SEAHIVE system, the development of its design is conducted based on a series of physical tests at the intersection of coastal, material and structural engineering. First, the outer profile and void configuration of SEAHIVE elements are investigated through tests in the SUSTAIN tank (Fig. 4) where the loads applied on the different element variants under various conditions of wave and wind action are defined in combination with evaluations of the element's performance related to wave energy dissipation and wave transmission effects. Elements are thus tested under a range of wind speeds from 0 to 70 m/s, which corresponds to wind-wave conditions from tropical storm to hurricane category 5 with varying water levels from partially submerged to fully submerged elements. The pressure on the elements is measured using pressure sensors throughout the element length, while the system performance is evaluated based on measurements from wave gauges (UDMs and vertical wire gauges) and current velocity meters (Acoustic Doppler Current Profiler behind and in front of the elements). Measurements of wave height and current velocity are employed to estimate transmission effects as well as sediment transportation rate and wave induced flow.

Fig. 4. View from inside the SUSTAIN tank (left) and SEAHIVE units ready for testing (right).

Based on the experimental load definition and the system performance evaluation, a series of SEAHIVE models will be produced using Fiber Reinforced Concrete (FRC). The models will entail additional non-corrosive reinforcement in the shape of Basalt Fiber Reinforced Polymer (BFRP) and Glass Fiber Reinforced Polymer (GFRP) strands for structural integrity, transportability, deep-stacked installation, and wave impact resistance. Moreover, the models will be designed for construction with traditional pipe making equipment at any precast facility promoting thus low-cost manufacturing. In addition, material tests will be performed to optimize sea-concrete mixes for improved robustness against wave loads, eased constructability, and marine compatibility. Models under different configurations will be tested at the SUSTAIN tank where pressure, wave height and current velocity measurements will be used to investigate key system parameters such as the element orientation, distance, and offset (Fig. 5).

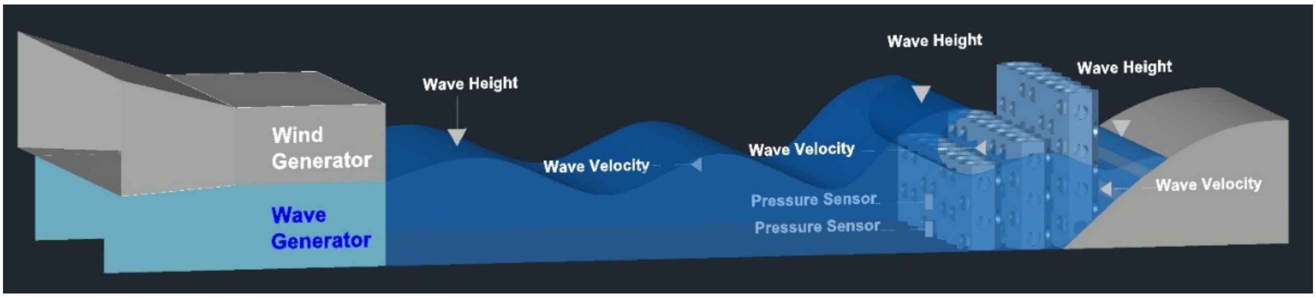

Fig. 5. Illustration of the physical testing of the SEAHIVE system at SUSTAIN Facility.

4. Discussion

Physical testing focuses on the experimental load definition and performance evaluation through pressure, wave height and current velocity measurements on physical models tested in the SUrge STructure Atmosphere Interaction (SUSTAIN) Facility under varying wave and wind conditions. Testing conditions were defined based on wave-history data from four locations (zones) in United States (Tab. 1). Wave data were explored to define similarity between prototype structures in the selected locations and the experimental models in SUSTAIN through a dimensional analysis of the Froude number since in wind generated waves gravity typically plays the most important role (Kamphuis, 2010).

Tab. 1. Wave characteristics in selected locations in U.S. according to National Data Buoy Center

Station No.	Location	H_s(m)	T_d(sec)
42095	Satan Shoal, FL	1.00	7.00
42067	University of Mississippi, MS	2.27	6.70
BTHD1	Bethany Beach, DE	0.85	8.48
46012	24NM SSW of San Francisco, CA	2.56	12.00

*H_s and T_d are significant wave height and dominant wave period, respectively

The selected scale for the experimental models is 1/5. Therefore, different parameters such as wave height, wave period and water depth are adjusted following this length scale. Tab. 2 shows the experimental conditions that are designated for the first phase of this study. The wave characteristics in Tab. 2 correspond to simple periodic wave conditions in which the Froude numbers in the models and prototype have similar values. In addition, wave conditions based on the JONSWAP spectrum model were employed for the same dominant wave periods and wave heights for still water depths of 45 and 65 cm in order to also consider irregular wave conditions.

Tab. 2. Experimental condition for the phase 1 of the study

No.	Parameter	Values Considered
1	Wave Period (sec)	1.5, 3 and 5
2	Wave Height (cm)	10, 20 and 30
3	Water Depth (cm)	45 and 65

In the second phase of the experiment, SEAHIVE group elements will be subjected to similar wave conditions as well as to combined wave and wind action with winds varying from tropical storm to Saffir-Simpson Hurricane category 5 in order to examine the performance of the proposed system design under extreme conditions.

5. Conclusion

In the absence of universally accepted guidelines for defining the combined wave/wind loads under extreme conditions for complex shoreline protection systems and evaluating their performance, this paper proposes a test-driven approach for the design of an efficient and ecofriendly seawall system (SEAHIVE). The SEAHIVE system is based on perforated tubular elements that allow passage of water flow under surging or breaking waves dissipating thus wave energy within the system. The design of the system is conducted through a series of physical tests in the SUrge STructure Atmosphere Interaction (SUSTAIN) Facility under varying wave and wind conditions. Physical tests are defined through a dimensional analysis based on the Froude number. Moreover, auxiliary biocompatibility studies related with material composition and structural complexity combined with the experimental testing at SUSTAIN can further enhance the design of the proposed system towards a shoreline protection structure with increased efficiency and enhanced biocompatibility features.

Acknowledgements

This material is based upon work supported by the National Cooperative Highway Research Program (NCHRP) Highway IDEA program (IDEA Project NCHRP-213).

References

American Society of Civil Engineers, 2016. Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 7-16). American Society of Civil Engineers.

Bergen, S.D., Bolton, S.M. and Fridley, J.L., 2001. Design principles for ecological engineering. Ecological Engineering, 18(2), pp.201-210.

CEM, USACoE. 2008. Coastal engineering manual..

Chapman, M.G. and Blockley, D.J., 2009. Engineering novel habitats on urban infrastructure to increase intertidal biodiversity. Oecologia, 161(3), pp.625-635.

Coastal Engineering Research Center (US). Shore protection manual. Vol. 1 & 2. Corps of Engineers, 1973.

Donelan, M.A., Haus, B.K., Reul, N., Plant, W.J., Stiassnie, M., Graber, H.C., Brown, O.B. and Saltzman, E.S., 2004. On the limiting aerodynamic roughness of the ocean in very strong winds. Geophysical Research Letters, 31(18).

FEMA P-55, Coastal Construction Manual: Principles and Practices of Planning, Siting, Designing, Constructing, and Maintaining Residential Buildings in Coastal Areas, 4th Edition (2011)

Gilbert, J. and Vellinga, P., 1990. Coastal zone management.

Gittman, R.K., Fodrie, F.J., Popowich, A.M., Keller, D.A., Bruno, J.F., Currin, C.A., Peterson, C.H. and Piehler, M.F., 2015. Engineering away our natural defenses: an analysis of shoreline hardening in the US. Frontiers in Ecology and the Environment, 13(6), pp.301-307.

Gittman, R.K., Peterson, C.H., Currin, C.A., Joel Fodrie, F., Piehler, M.F. and Bruno, J.F., 2016. Living shorelines can enhance the nursery role of threatened estuarine habitats. Ecological Applications, 26(1), pp.249-263.

Hoffman E. The cost of shoreline stabilization, south Atlantic Living Shorelines Summit, Governor's South Atlantic Alliance available online (accessed July 17, 2018): http://southatlanticalliance.org/wp-content/uploads/2016/04/17-Hoffman-The-Costs-of-Shoreline-Stabilization.pdf

Hom-ma, M. and Horikawa, K., 1964. Wave forces against sea wall. Coastal Engineering Proceedings, 1(9), p.31.

Hom-ma, M. and Horikawa, K., 1965. Experimental study on total wave force against sea wall. Coastal Engineering in Japan, 8(1), pp.119-129.

Kamphuis, J.W., 2010. *Introduction to coastal engineering and management* (Vol. 30). World Scientific.

Soloviev, A.V., Lukas, R., Donelan, M.A., Haus, B.K. and Ginis, I., 2014. The air-sea interface and surface stress under tropical cyclones. Scientific reports, 4, p.5306.