Investigation of Mangrove Compliant Structural Systems in Association With Human Coastal Development

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1.0 Analysis of Tropical Coastline and built Environment Context

Economic expansion of coastal urban centers places large populations into direct land-use competition with native shoreline ecosystems. As a result, mangrove forests, tropical and subtropical intertidal ecosystems[1], are currently being lost at a rate faster than the rainforests[2]. These unique shoreline habitats are highly adapted to the environment and essential to biodiversity linked to a complex network of land and marine ecosystems. Mangrove forests are responsible for the filtration of agricultural and urban runoff and provide a primary fish habitat essential to healthy populations of ocean fish stock[3]. An estimated 35% of the world's original mangrove cover is gone, with some countries having lost up to 80%, progressively exposing the world's shorelines to turbulent weather patterns[4]. By 2003, about half the world population (approximately 3 billion) was living in a coastal strip just 200 kilometers wide with intense urban development coinciding with population growth along tropical coastlines.[5]

Shoreline stabilization technologies are designed to brutally resist the dynamic environment that constitutes the coastal zone. These rigid coastal structures exposed to wave action cause scour: a phenomenon that occurs when wave energy meets a static body redirecting and accelerating water in turbulent motion that disrupts sediment particles[6]. These particles become waterborne and are then carried away from the shoreline by tidal action or the rebounding wave energy, increasing erosion rates near human structures.

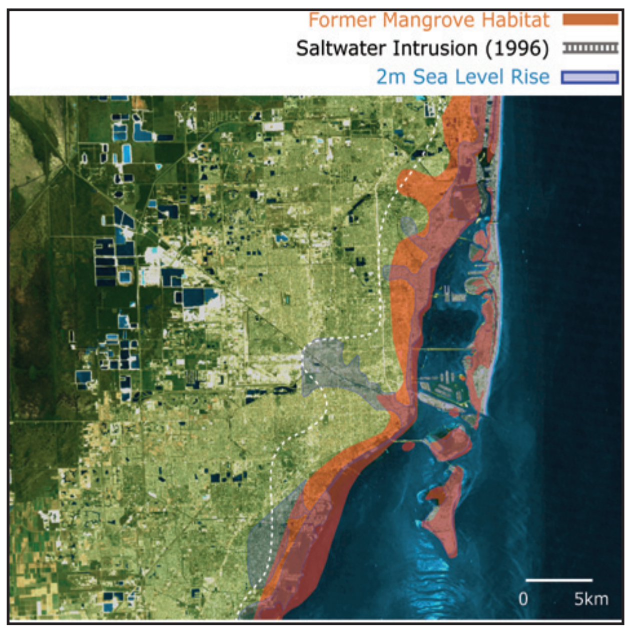

Fig. 1. Analysis of disrupted systems at the coastal interface, Miami, Florida[7]

Coastal structures that are exposed to extreme weather conditions are susceptible to elevated insurance rates, and regional-scale damage from especially severe storms leaves monetary and infrastructure resources exhausted, thus reducing available funds for coastline reparations. Current trends indicate a negative dual-impact scenario, where the replacement of native shoreline vegetation with urban development places large populations and cities at risk of wave impact and flooding while simultaneously degrading the biological components that support the larger coastal ecology. [Figure 1] These urban structures located at the shoreline interface are in urgent need of innovative re-design to address the impending environmental collapse and vulnerable exposure of tropical shoreline communities.

2.0 Research Description

2.1 Conceptual Approach

Man-made structures have historically been built to remain fixed within the landscape, resisting the dynamic biological flows and climatic phenomena that shape the land. These architectural and urban planning conditions host an expanding population and attempt to subdue and maintain an inherently changing landscape. As a result, human-engineered systems create impedances to the morphological characteristics of the environment and disrupt the continuity of critical nutrient and hydrological flows across the landscape. [Figure 2a]

In contrast to man-made rigid structures, environmental systems maintain flexibility across multiple scales. Ecosystems demonstrate 'soft edges' and gradual transformations where overlapping conditions blend what would be considered nominal entities. Transitional zones merge criteria into hybrid conditions such that specific boundaries become indiscernible (estuarine environments for example). Vegetation bends and sways as a result of flexible geometries and materials, and cellular growth patterns have evolved to form composite systems that contain varying levels of resistance to dynamic environmental forces[8]. Vegetation systems interact at differing spatial and time scales of compliance (cellular, plant, ecosystem) to produce the complex morphological behavior of the landscape. [Figure 2b]

Native landscape systems exhibit certain characteristics that have developed in response to environmental forces. Shorelines in tropical regions are subject to extreme weather events and a turbulent environment, and vegetation systems exposed to these conditions have specific physical properties that promote existence within these regions. Mangroves provide coastal defense and dissipate the energy and size of waves as a result of the drag forces exerted by multiple tangled roots and branches[9]. Under normal sea conditions and during hurricanes and tropical storms, at least 70-90% of the energy of wind-generated waves is absorbed, depending on how healthy the ecosystems are in terms of physical and ecological characteristics[10]. Mangroves fail non-catastrophically during turbulent weather as a result of the networked connectivity that is vital to their subsistence. Regional assessment of the aftermath post 2004 Indian Ocean Tsunami revealed greater damage to communities without significant vegetation barrier between land and sea as a result of wave impact[11].

In contrast to the effects of scour on structures, coastal vegetation acts as a permeable and energy-absorbing interface with the ocean, reducing the effects of wave impact by flexing and maintaining

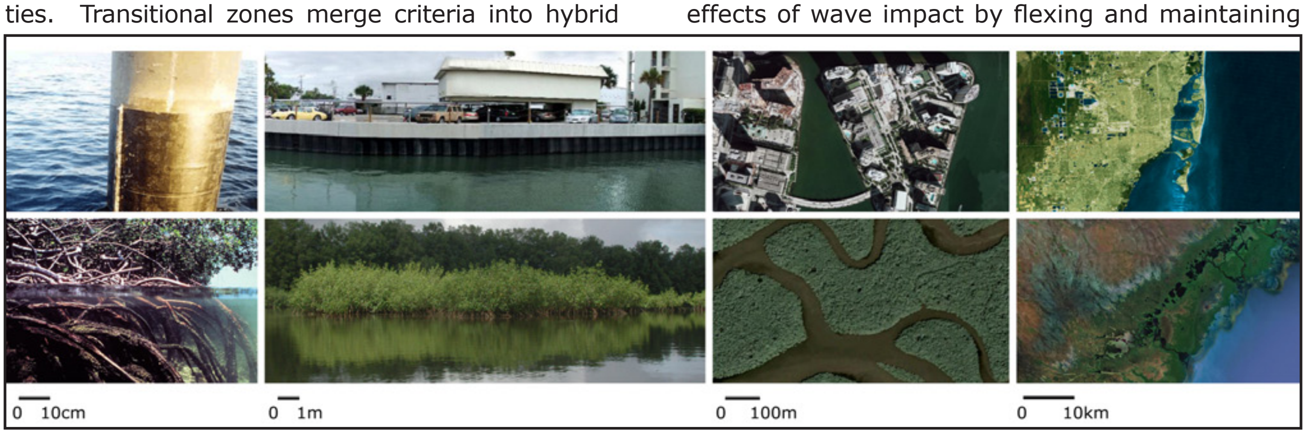

Fig. 2. Corresponding scales of (a) urban coastal development and (b) mangrove ecosystem, South Florida[8]

shoreline integrity through embedded root geometries. Mangroves help to stabilize coastal land by trapping sediment washed down in rivers or from more general land-based surface run-off. These tree structures are natural shoreline filters, capable of absorbing pollutants, such as heavy metals and other toxic substances, in addition to nutrients and suspended matter in the water, which lends to the integrity and resilience of the shoreline ecology[12]. The cumulative mangrove ecosystem acts as continuous structural matrix, often kilometers in length, between saltwater and freshwater environments, preventing many pollutants from migrating to deeper water as well as holding back sediment that provides a retardation factor to the inland migration of seawater.

Mangrove forests have evolved in response to a multitude of environmental forces, resulting in physical characteristics that benefit survival. These plants contain inherent characteristics that contribute to 'controllable compliance' whereby flexible geometries and materials allow displacement under a variety of environmental stresses. Mangrove root and branch networks create a continuous structural landscape, and this flexible woody labyrinth distributes energy across the landscape in an interdependent manner. The evolution of these physical geometries is a product of the complex interaction between living and nonliving systems.

Built structures that emulate native vegetation would produce environmental conditions similar to the landscape prior to human development and significantly alter the current relationship between building and landscape. By doing so, built conditions could host biological networks, and in addition, our built environments would benefit from the regenerative and energy-absorbing properties of integral native vegetation systems. In order to incorporate mangrove characteristics within human systems, certain parameters of the mangrove ecosystem were modeled to identify the patterns and scales at which these criteria could be feasibly integrated within large-scale urban structures.

2.2 Modeling of Shoreline Criteria

The physiology of the mangrove ecosystem is determined by various feedback cycles among biota, landforms, and water flow[13]. These factors interact to produce the underlying relationships that form the basis to the mangrove ecosystem. In order to visualize the dynamic variables of these systems, parametric modeling served as a database to contain the complex associations and multiple feedbacks attendant to the mangrove shoreline. Parametric modeling is necessary to manage complex conditions that result from multiple systems overlap within interdisciplinary research, and the intricacies of environmental systems produce complex geometries and changing conditions that are otherwise difficult to track within standard design tools. These modeling strategies attempt to bridge between discipline-specific data sets and provide a framework by which information exchange can be facilitated. In addition, criteria was modeled with 3d parametric design tools to connect the analytical procedures with data representation in the experiment, with the intention to uncover dynamic patterns that occur at varying spatial and temporal scales as a result of the interactions of multiple systems.

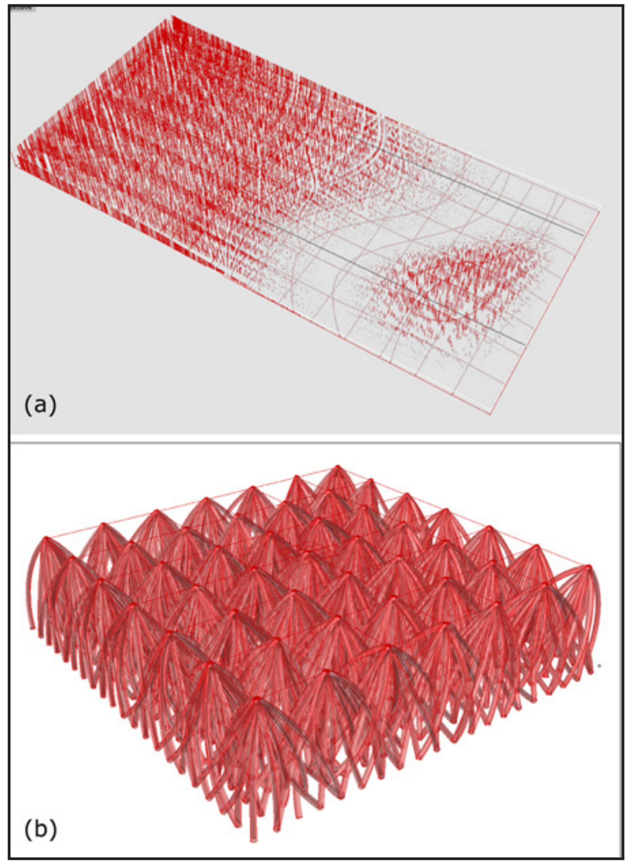

Fig. 3. Parametric modeling of mangrove ecosystem criteria at multiple scales: (a) ecosystem range and behavior, and (b) mangrove root characteristics

Characteristics of native mangrove ecosystems were used to model the initial shoreline conditions. [Figure 3] Healthy (very dense) mangrove forests exhibit an approximate density of upper trunks of 10/m^2 and lower trunks of 30/m^2 (or 1:3) where the lower and denser regions are responsible for the tree's exceptional wave break capacity[14]. Mangroves vary from region to region, so the diameters of roots, trunks and branches, as well as root densities, were set as variables in the model and could be adjusted according to species or local ecosystem conditions.

These parameters were then combined with human requirements for structural stability under lateral and gravitational loading. Rigid members were integrated within the matrix to provide stiffness where programmatic loading would occur. The result was a hybrid system; flexible and interdependent structure capable of supporting multiple scales of urban program. This system was then assessed for performance under exposure to a simulated coastal environment.

2.3 Experiment: Compliant Interconnected Structures

In order to quantify shoreline integrity, two major components for testing are critical to the research: modeling of (i) environmental forces acting on a shoreline condition, and (ii) the physical response of the shoreline to the environmental loading. The relationship between these parameters is ultimately expected to inform coastal construction strategies as a function of wave break capacity, structural integrity, and ecosystem management. Mangrove trees respond to wave impact by distributing the load across multiple trees [Figure 4a], and the parameters responsible for this behavior and described above were incorporated with human structural requirements in the model. The continuous structural landscape model was then subjected to wave impact to assess physical response and environmental conditions that resulted. [Figure 4b & c]

Specific flexible parameters were incorporated into a three-dimensional structural grid system for this experiment. The orthogonal grid matrix was given permissible range of movement at vertices and associated with a velocity reduction gradient identified through fluid analysis wave impact simulations. Structural grid deformation was controlled through extents that were defined by material properties and assigned to specific components within the grid. The experiment was executed as a starting point for further analysis of the relationship between human and environmental criteria at the coastline.

2.4 Conclusions

Coastal vegetation in tropical regions is exposed to an array of extreme conditions as a result of turbulent weather patterns, and the advantages of compliant systems over their rigid engineered counterparts are evident. Tree canopies exposed to strong winds are able to reconfigure and adjust to reduce drag loads on the multiple branches, resulting in a uniform and streamlined shape[15]. In-

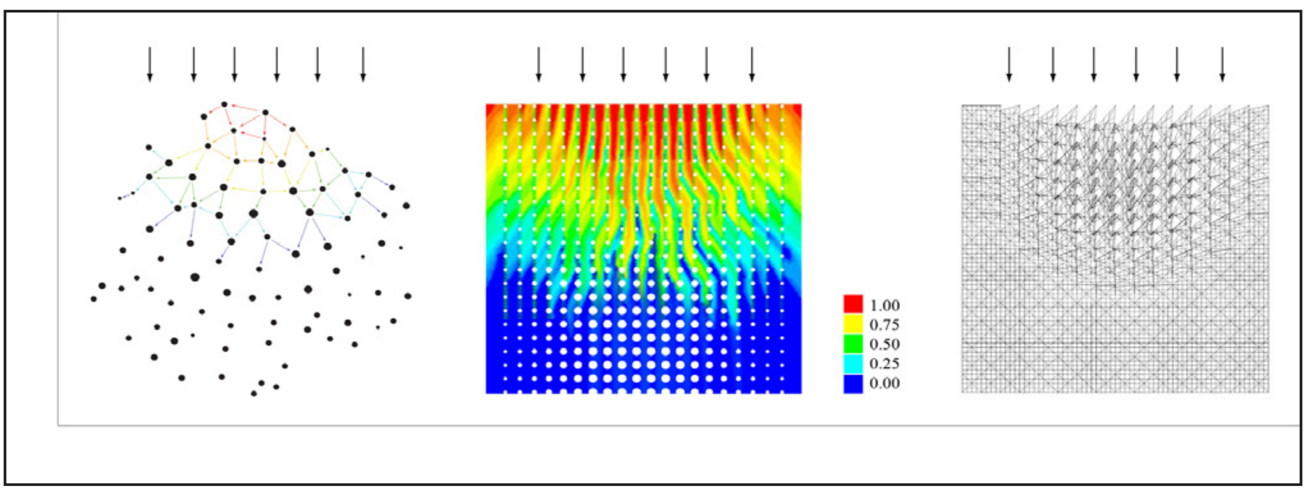

Fig. 4. Analysis of interaction between environmental conditions and structural response: (a) diagram of wave impact on tree cluster, (b) wave impact on structural system, (c) structural response to impact

terior branches are protected by the more pliable leaves and smaller twigs that are exposed at the exterior of the tree. Another advantage is that flexible systems can be shock absorbers for more substantial primary structural members. Sudden impact on a rigid structure as a result of extreme environmental conditions can produce momentary stresses much higher (sometimes double) that of normal loading[16]. Structural systems able to reconfigure and adjust to environmental forces can distribute loading, lowering the effective magnitude of the initial impact.

Composite structures enable 'near-calculable' performance under an array of environmental stresses. In addition, hybrid systems can address multiple simultaneous criteria by utilizing material placement and orientation. Structural displacement within the models can be calibrated to the necessary levels of displacement and designed in accordance with a material's flexural and torsional strengths.

In the experiment, flexible components were assigned permissible displacement values to contribute to velocity reduction by absorbing energy. Compliant strategies were used in this application to explore a permeable and flexible structural interface between human-engineered and environmental systems at the shoreline. The drag produced by this system is anticipated to be similar to that of a mangrove forest, and the environmental conditions created by the flexible structure would likely create mangrove-like habitat, although testing for biological response is necessary.

3.0 Discussion

Global urban development patterns are endangering tropical coastline forests at unprecedented rates, with catastrophic consequences for all life forms. In terms of human development, the loss of protective mangrove forests and wetlands is progressively exposing conventional civil coastline structures of all scales and types to damage and catastrophic failure from the increasingly extreme weather conditions associated with global warming. Human structures in tropical coastal regions are failing to protect shoreline communities and becoming increasingly difficult to financially underwrite through conventional property insurance, though development is still occurring in these regions. These constructed landscapes are extremely vulnerable, and data on the behavior of the associated ecological systems is still irregular and relatively sparse. Factors such as these provide powerful incentives to develop a new paradigm to model and design civil coastline structures. This paradigm requires extended interdisciplinary groups of scientists and engineers, working on questions that span large ranges of physical and temporal scales to share data and computational modeling procedures with decision makers who are currently designing and implementing the next generation of coastal engineering structures.

This imperative creates both cultural and technical difficulties. The obvious difficulty of translating theoretical models to real landscapes with potentially huge numbers of parameters is compounded by questions such as how multi-scale, multi-resolution across-discipline models may be employed to develop integrated design tools. The inference of patterns from the integration procedures is critical to the optimal design of environmental structures and to shift the currently unsuccessful paradigm for conventional civil coastline structures.

Although the context for this research is performance of 'built ecologies' along tropical coastlines, the research has wider implications for any interdisciplinary framework whereby the urgent shift to address mechanistic and large-scale practical environmental challenges has required simplification of complex models to transfer information across scales. It is anticipated that this research will contribute to the knowledge base of multi-scale dynamic and complex modeling, with particular pertinence to shoreline erosion control and ecosystem restoration. The long-term scientific goal is the development of methods to predict the response of ecosystems to a series of interdependent structural systems that simultaneously support sustainable urban scale development along with flourishing indigenous flora and fauna, while dissipating the dangers from extreme weather events and rising sea levels.

Environmental flows reinstated and consistent with the mangrove ecosystem would have valuable consequences. Mangroves provide ecological services that contribute to human food production as well as adjacent marine and land-based ecosystems. Coastal communities that operate mostly within local economies rely on the resources associated with the mangrove ecosystem without contingency plan for additional sustenance. Mangrove detritus production is about 1 kg litter/m^2 annually, with a portion of that exported with the tide, forming the basis of a complex food web that extends into other ecosystems, such as coral reefs and sea grasses[17]. The habitat provided by mangroves acts as spawning and nursery areas, sheltering species that live in other ecosystems as adults[18]. Our understanding of ecological processes and how they relate to the resulting services has widespread applicability in the pursuit of sustainable human coastal development.

Fig. 5. Futurization of compliant structural landscape and urban development

In order to promote the existence of living systems in association with built conditions, engineered structures must integrate environmental processes at the fundamental and physical levels. These environmental systems, which can and should influence architectural tectonics, form the understructure to complex ecological networks, and ultimately should be used to inform regional design strategies for architectural and engineering systems that will be subjected to the same environmental conditions. It is this comprehensive approach that will ultimately secure human habitat as part of the evolving landscape.

ENDNOTES

1. Alongi, Daniel M. *The Energetics of Mangrove Forests* Springer. 2009.

2. The United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC). *In the front line: shoreline protection and other ecosystem services from mangroves and coral reefs*. UNEP-WCMC: Cambridge, UK. 2006.

3. Tomlinson, P.B. *The botany of mangroves* Cambridge University press. 1986.

4. UNEP-WCMC. 2006

5. United Nations Population Fund. *State of the World Population 2007*. 2 July, 2008; <http://www.unfpa.org/swp/2007/english/introduction.html>

6. Gerwick, Ben C. Jr. *Construction of Marine and Offshore Structures* CRC Press: Boca Raton. 2000.

7. Data from: (1) Google Earth, (2) The United States Geological Survey: South Florida Information Access. *Impact of Anthropogenic Development on Coastal Ground-water Hydrology in Southeastern Florida, 1900-2000*. 20 November 2009, <http://sofia.usgs.gov/publications/circular/1275/index.html>, and (3) National Oceanic and Atmospheric Administration. *Biscayne Bay: Environmental History and Annotated Bibliography* US Department of Commerce: Silver Spring, Maryland. 2000. p 12. 20 November 2009, <http://www.aoml.noaa.gov/general/lib/bbdl.html>

8. Image sources from left to right: (a) <http://www.slickbar.com/CCI/installation_photo_reports/lake_pontchartrain.asp>, <http://www.antinorimanagement.com/Pictures.html>, Google Earth, NASA Visible Earth and (b) NOAA, <http://jrscience.wcp.muohio.edu/tropics/costaricaimagecollection.html>, Google Earth, Google Earth.

9. Massel, S.R., K. Furukawa, and R.M. Brinkman. “Surface wave propagation in mangrove forests” in *Fluid Dynamics Research* Vol. 24, 1999. p. 219-249.

10. UNEP-WCMC. 2006.

11. Danielson, F., Mikael K. Sorenson, Mette F. Olwig, Vaithilingham Selvam, Faizal Parish, Neil D. Burgess, Tetsuya Hiraishi, Vagarappa M. Karungaren, Michael S. Rasmussen, Lars B. Hansen, Alfredo Quarto, Nyoman Suryadiputra. “The Asian Tsunami: A Protective Role for Coastal Vegetation” in *Science* Vol. 310, 2005.

12. UNEP-WCMC. 2006.

13. Mazda, Y., E.Wolanski, B.King, A. Sase, D. Ohtsuka, and M. Magi. “Drag force due to vegetation in mangrove swamps” in *Mangroves and Salt Marshes* Vol. 1, No. 3, 1997. p 193-199.

14. Massel et al. 1999.

15. Vogel, S. Drag and reconfiguration of broad leaves in high winds. *Journal of Experimental Botany*, Vol. 40, 1989. p 941-948.

16. Ennos, A.R. “Ch. 2: Compliance in plants” in *Compliant Structures in Nature and Engineering* Ed. C.H.M. Jenkins. WIT Press: Boston. 2005. p 21-37.

17. UNEP-WCMC. 2006.

18. Tomlinson. 1986.