

2012

Biologically dominated engineered coastal breakwaters

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BIOLOGICALLY DOMINATED ENGINEERED COASTAL BREAKWATERS

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
In partial fulfillment of the
Requirements for the degree of
Doctor of Philosophy

in

Interdisciplinary Programs in Engineering Science
The Department of Biological and Agricultural Engineering

by

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M.S., California State University, 2002
August 2012

DEDICATION

This Doctorate of Philosophy Dissertation is dedicated to my grandfather Wallace L. Keller.

ACKNOWLEDGMENTS

I would like to thank my family for their love, dedication, and support; and also Dr. Steven Hall as a friend and an advisor during this Ph.D. Dissertation. I would also like to thank my graduate faculty committee of Dr. Richard Bengtson, Dr. Ron Malone, Professor Jim Wilkins (J.D.), Dr. John Supan, as well as Dr. Len Bahr, Dr. Bob Beine, Dr. Jim Chen, Dr. Dubravko Justic, Dr. Harry Roberts, Drs. Jerome and Megan Lapeyre, Dr. Ed Laws, Dr. Ralph Portier, Dr. Teresa Gutierrez Wing, Dr. Tyson Rupnow, the LSU AgCenter, ORA Technologies LLC, Wayfarer Environmental Technologies, and certainly all faculty and staff of the Department of Biological & Agricultural Engineering at Louisiana State University. Special thanks to Mr. Brac Salyers of the Louisiana Department of Wildlife and Fisheries and the staff of the Louisiana State Rockefeller Wildlife Refuge. Special thanks to Ms. Paula Ouder of the Louisiana Sea Grant College.

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ABSTRACT

Coastal land loss in Louisiana is occurring at astounding rates. New technologies for shoreline protection are needed that incorporate traditional engineering designs with natural systems (e.g., oyster reefs). Under optimal environmental conditions eastern Oysters (*Crassostrea virginica*) can biologically dominate artificial concrete reef structures used as coastal breakwaters within the intertidal zone. These reefs can also serve as oyster broodstock sanctuaries providing a nexus to the public oyster grounds benefiting the aquaculture industry. The use of biologically dominated, engineered breakwaters may provide a viable solution to coastal restoration and shoreline protection challenges. Biologically dominated coastal breakwaters can be integrated into coastal zone management strategies to preserve coastal resources by offering compatible uses across multiple disciplines. An experimental study was conducted at Rockefeller Wildlife Refuge monitoring material strength, sediment accretion, and oyster biometrics on high-relief, three-dimensional artificial reefs using concrete scaffoldings for growth substrates. Spat plate data on these reefs indicated the spring spatfall exceeded 10,000 spat/m² in some locations. Oyster shell height measurements of 50 cm were recorded after six months growth, with oyster counts exceeding 500 per m² on the artificial concrete modular breakwater reefs. Alternate concrete substrates (i.e., vitrified expanded clay) showed optimal strength and weight when compared to traditional higher density aggregates, weighing less than 50% by volume with no statistically significant difference in ASTM 39 standards for compressive strength (3,328 lbs with P<.001). Biologically dominated concrete structures showed a significant increase in ASTM 78 standards for flexural strength over time from an initial 28-day curing load of 100 lbs to loads of 479 lbs in six months and 1,344 lbs in two years. Pilot scale breakwater emplacements dominated by biological growth accumulated nearly 4 m³ of sediment over four

years. Heavy and light density reef emplacements installed for less than one year accreted 1.6 and 0.37 m³ of sediment, respectively, relative to baseline cross-shore transects with no breakwater emplacements.

CHAPTER 1: BIOLOGICALLY DOMINATED ENGINEERED BREAKWATERS FOR COASTAL PROTECTION AND ECOLOGICAL RESTORATION

Louisiana, like many coastal areas (e.g., Netherlands, Bangladesh, and the Maldives), is experiencing significant land loss across much of its coastal regions. The state contains 40% of the nation's wetlands but suffers 80% of the nation's wetland loss. This disproportion can be attributed to factors such as limited sediment supply, hurricanes, land subsidence, sea level rise, and, in some cases, saltwater intrusion that is detrimental to marsh and wetland vegetation. These coastal regions are important to local and global economies alike. Many local inhabitants rely on the Louisiana coastal zone as a way of life for food, recreation, and jobs. On a global level, entire ecosystems can be changed or diminished by a decline in coastal wetlands, wildlife, fisheries, and oyster populations. In addition to their commercial value as a food source, oysters can serve many functions in protecting the coast, from serving as an ecological species to reducing wave energy with the colonial intertidal reefs they form. Employing oysters in the battle against coastal land loss is an economically and environmentally sustainable biologically engineered approach to coastal zone management that can be facilitated through the use of artificial reefs to serve as coastal breakwaters to reduce wave energy and provide shoreline protection.

1.1 Introduction

The U.S. Gulf of Mexico coast is experiencing land loss due to a variety of natural and anthropogenic factors. This loss is especially prevalent in coastal Louisiana due to a combination of dwindling system sediment supply, wave energy dynamics, hurricanes, sea level rise due to climate change, and land subsidence. Figure 1.1 below shows marsh land loss near

Indian Point in Vermilion Bay and recent shoreline protection measures. This localized land loss is due, in part, to normal wave action against the marsh grass that undermines the integrity of the shoreline and strips away pieces of marsh, which can actually be seen floating in the bay. Once the overlying plants are washed away, the soil quickly follows, and the process is continual and is exacerbated by storm events and higher wave energies. Natural oyster reefs historically provided some protection against this wave-induced erosion, but the land in this region continues to subside as sea level rises, and no natural riverine sediment input exists to replenish the loss.



Figure 1.1 a, b: (a) Land loss in Vermilion Bay, La. (2011) and (b) commercial scale artificial breakwater oyster reefs used for shoreline protection (2012)

Engineered breakwater structures are a common and simple way to combat this rapid land loss because they can dissipate wave energy and promote sediment accumulation. They also serve as artificial reefs when dominated by biological growth, which enhances aquatic environments and ecosystems. Biologically dominated, engineered reef technologies can provide multiple lines of protection against land loss in coastal Louisiana, while offering many other value added ecosystem services. Such systems can dissipate wave energy and allow sediment accumulation

while providing substrate for oyster growth. Oyster growth on these manufactured reefs reinforces their structural integrity as a breakwater and increases wave energy dissipation and shoreline protection. Oysters also offset the effects of land subsidence and structure settlement, as they grow vertically in the intertidal zone, adding height to the breakwater. Biologically dominated engineered reef technologies are relatively simple in their conception; however, additional research is needed to better understand breakwater dynamics, reef geometries, sediment accumulations, oyster biological growth, carbon sequestration, optimal structure composites, and settlement.

Research was conducted on pilot scale experimental reef sites at the Louisiana State Rockefeller Wildlife Refuge to further qualify and quantify the use of biologically dominated reef technologies as engineered breakwater structures for multiple lines of protection, to mitigate coastal land loss, and to facilitate coastal restoration and protection. The design of biologically dominated engineered coastal breakwaters can be optimized relative to material strength and geometries, oyster biometrics, sediment accretion, and carbon sequestration potential.

1.2 Background

Oysters are said to be ecosystem engineers, but the study of the positive effects that high-relief reefs provide in reducing wave energy in the coastal zone is a relatively new science human engineers are exploring. Bioengineered oyster reefs provide a method to create a living shoreline with self-sustaining qualities that differentiate them from traditional nearshore rock breakwater structures. Research has focused for nearly a decade on the design of biologically dominated, engineered intertidal breakwaters that serve as artificial oyster reefs and dissipate wave energy and trap sediment near shore within the coastal zone (Hall, 2009). This sediment allows land to

form where native grasses can take root. Colonial in nature, oysters serve as a keystone species, congregating to form reefs and provide food, shelter, and life within the coastal zone. Not only are these bivalve mollusks a key to the survival of many plant, fish, and wildlife species, they are a local delicacy distributed throughout the world for human consumption.

Historically along the Mississippi delta, water flowed from the river into the Gulf of Mexico, carrying sediment that settled forming cheniers and creating land that eventually became barrier islands. These islands helped protect the coastal zone during hurricane events. The sediment deposited during seasonal flood events also fueled vegetative growth in the marshes and wetlands and reduced the effects of saltwater intrusion. Minor variations in salinity brought about by annual flood events were also healthy for the oyster populations, providing optimal conditions for growth and minimizing disease and predation. With the Mississippi River now controlled by the U.S. Army Corps of Engineers and channelized with levees, human lives and property are better protected from flooding. However, negative environmental and ecological impacts have been evident for some time. The river is dredged to remove sediment to allow for navigation; fewer floods occur within the marshes; and saltwater is encroaching on the wetlands, altering and in some cases destroying the web of native species. Marsh dredging and the digging of channels by the oil and gas industry have also compounded wetland loss by fragmenting the land mass and allowing greater saltwater intrusion.

Coastal land loss in Louisiana is occurring at astounding rates due to lack of sediment supply, lack of natural shoreline protection, and storm events. The lands formed by historic sediment deposition are subsiding and eroding, which increases vulnerability to land loss from storm events. Even the smallest storm causes land loss, with larger hurricane events shearing and scouring entire marshes. Climate change and sea level rise exacerbate the effect of subsidence,

leaving little natural defense against coastal erosion. However, native grasses and oyster reefs can provide a natural form of shoreline protection.

Oyster reefs can adapt to and survive some of the previously mentioned causes of land loss. Oysters tolerate a wide range of salinity in the intertidal zone. They filter water, and they feed on plankton and algae that are fueled by nutrients in the water. They grow within the intertidal zone and can compensate for sea level rise and land subsidence by vertical growth. They are colonial, fecund, sessile, and hermaphroditic in nature, typically spawning in the spring and fall, depending, in part, on water temperature and salinity variations. Oysters form reefs within the intertidal zone that can armor shorelines and dissipate wave energy by promoting wave refraction, a coastal engineering term referring to a shoaling effect waves encounter when encountering bottom friction.

Wave refraction generally occurs as water depth decreases as the waves approach the shoreline. When waves approach the shoreline and pass over oyster reefs, the bottom friction increases with decreasing depths and an intertidal breakwater effect occurs. This reduction in wave energy allows leeward sediment accretion behind the reef and a “tombolo” or salient formation follows. This sediment accumulation accretes from the shoreline and buffers the land formation, allowing plants to root, which further strengthens the shoreline. This “living shoreline” effect is attributed to the oyster reef.

Oysters engineer reefs that can serve as biologically dominated intertidal breakwaters. Facilitating this reef development with engineered structures is called Biocoastal Engineering. Bioengineered oyster reefs facilitate biological growth by providing a substrate or hard surface upon which oyster larvae can settle. Oyster larvae typically settle on older oysters, forming

colonies. Oyster reefs cultivated for harvest are often created with oyster shells or other materials that allow for larvae settling. These shells or other base materials are called “cultch.” Research has investigated the use of concrete as a material to facilitate this reef development because it provides an increased surface area with substrate suitable for oyster settlement, colonization, and growth (Hall, 2009). These concrete forms are hollow, cylindrical, circular modules that can be deployed in the intertidal waters of the coastal zone. The oysters settle on and colonize these ring-shaped refuges, where they continue to grow and ultimately increase the function of the reef as a biologically dominated breakwater. These biologically dominated breakwaters serve many ecological functions and aim to address shoreline protection by reducing wave energy through oyster growth.

1.3 Bioengineered Breakwaters as Artificial Oyster Reefs

Oysters are ecosystem engineers, dominating structural and ecological components of estuaries and fueling coastal economies—one or a few species can produce reef habitat for entire ecosystems (Beck, 2011). Previous work (e.g. Campbell, 2006; Ortego, 2008; Hall, 2009; and Dehon 2010) has shown that by providing lightweight, three-dimensional structures (rings, bars, and other shapes in the water column), growth of oysters (*Crassostrea virginica*) and other species can be encouraged at a number of field sites in the Gulf of Mexico.

The inclusion of organic materials in the concrete mix used to make these structures can result in the release of organic acids and other organic chemicals, which encourages veliger-stage (mobile) larval oysters to set on the structures (settle and permanently attach). This settling and attachment of pediveliger-stage oysters onto a substrate is called “spatfall.” Oyster survival is influenced by shape, rugosity (wrinkles), and other structure features, while oyster growth slowly

locks the structures together, increasing overall structural strength. In this way, relatively lightweight (<10% of comparable rock breakwaters, with experimental structures <4% of similar breakwaters) and weak (typically 500-3,500 psi) concrete aggregate structures can become very strong once they are biologically dominated with one to three seasons of oyster growth. These structures show both horizontal and vertical mollusk growth, and data suggests that nonlinear and increasing growth rates occur over time. This is likely due, at least partially, to increased net surface area over time as the reefs themselves grow through oyster colonization. Growth in excess of 5 cm/year in both vertical and horizontal directions has been observed on existing experimental pilot scale artificial concrete reefs (Dehon 2010).

Ecologically engineered artificial reefs have been used to enhance and encourage growth of oysters and other organisms in coastal protection and restoration projects. These reefs can serve multiple functions, including: food production, water quality enhancement, coastal protection and restoration, carbon sequestration, and habitat and ecological services. These reefs can also adapt to climate change, since they actually grow to new ocean levels. These reefs encourage growth of desired organisms and, in areas where regeneration of oyster populations are needed, can serve as an important source of oyster broodstock.

1.4 Coastal Engineering and Coastal Zone Management

Kamphuis (2008) traces the development of coastal engineering, drawing parallels with the history of civilization and the development of society in general. He recalls the impact of the enlightenment on science and society and describes the rise of the modern era, in which coastal engineering has its roots. Kamphuis (2008) explores the concepts of uncertainty, pluralism, and sustainability in attempting to find some direction in which to proceed with coastal education,

research and management within the postmodern environment. This leads to a new era of sustainable environmental design to complement traditional methods for coastal engineering and management. This new approach of integrated coastal zone management creates a cross-disciplinary environment that incorporates biological aspects of ecological restoration into coastal engineering.

Kamphuis (2010) traces developments in coastal/civil engineering practice and coastal/civil engineering education. He notes that engineering has changed substantially. What was once a generalist discipline has evolved into a collection of specialists trained in narrow fields. It introduces the changes over time from traditional to contemporary engineering and decision making and notes that today's engineers are not educated for the contemporary tasks they face. For viable sustainable solutions within the coastal zone of Louisiana, unique approaches must be considered to provide environmental and cost effective methods for coastal protection and restoration.

Traditional hard-structure engineering approaches may not be an environmentally or cost effective, sustainable solution to coastal protection, as many require intensive maintenance and fail to incorporate biological design scenarios that favor long-term environmental solutions. Multidisciplinary teams of scientists and engineers must emerge to face the political, socioeconomic, and environmental intricacies of coastal zone management. The bioengineered oyster reef is an emerging research topic and a significant tool that may fit the requirements of a new paradigm for viable solutions to coastal problems.

Combining the science of oysters and ecosystems with engineers' optimized design of biologically dominated breakwater structures creates a unique mechanism for coastal zone

managers to employ along the Gulf Coast. These types of biologically dominated structures do have limitations and are constrained by the very biological nature of their design and are restricted to use within the intertidal zone where oysters can survive. For example, certain environmental conditions must exist (e.g. water quality, temperature, and location within the water column) for the operational effectiveness of such structures to be realized. Sedimentation and overburden from hurricanes is also a design constraint that could limit the effectiveness of these structures. Finally, biofouling may occur, depending on the time of seasonal emplacements.

1.5 Coastal Erosion and Land Loss

Over the past few centuries, 25% of the coastal deltaic wetlands associated with the Mississippi delta have been lost to the ocean; the sediment load of the Mississippi River has been reduced by 50%; and it is estimated that an additional 10,000-13,500 km² of land will be submerged by the year 2100 from the effects of subsidence and sea level rise (Blum and Roberts, 2009).

Coastal erosion and mitigation are of major concern in Louisiana because of their potential to impact cultural heritage, socioeconomics, and the environment. Shore protection projects can moderate the long-term average erosion rate of shoreline change from natural or manmade causes to provide a wider sediment buffer zone between the land and the sea. Complete control of coastal flooding and erosion is a myth that gives a false sense of security, as man cannot control nature (USACE-CEM Part VI, 2006). An important area of concern is the restoration of environmental resources such as wetlands and oyster reefs lost to coastal erosion. In 1990, the U.S. Army Corps of Engineers was directed to consider ecosystem restoration when a federal project has contributed to ecosystem degradation (USACE-CEM Part VI, 2006). Nontraditional

technologies such as artificial breakwater reef structures are also being investigated in field experiments (USACE-CEM Part VI, 2006).

Coastal breakwaters, reefs, and wetlands all moderate the coastal sediment transport processes to reduce the localized erosion rates. These structures should be considered where chronic erosion is a problem and is caused by diminished sediment supply and lack of natural shoreline protection. The coastal setting is dynamic and influenced by land, water, and air interactions and processes. It is a regime of extremes, surprises, and constant motion, as the coast responds to changing conditions (USACE-CEM Part VI, 2006). Coastal erosion is a continual process along the Louisiana shoreline (Wilkins et al., 2008). The barrier islands and beaches from the Mississippi state line to Atchafalaya Bay are eroding, except for two sections, one at the eastern end of Grand Isle and the second at the western end of Timbalier Island (Frazier, 1967). Along the Chenier plain, accretion is occurring from the vicinity of Marsh Island, west approximately 25 miles into Vermilion Parish, and in Cameron Parish from the Mermantau River to west of the Calcasieu River (Coleman, 1966). In southwest Louisiana, the Rockefeller Wildlife Refuge is experiencing long-term shoreline retreat of 30 to 40 feet per year (Byrnes et al., 1995). Historic oyster reefs served to attenuate wave energy in this region, but loss of these reefs has exacerbated the land loss problem.

1.6 Climate Change and Sea Level Rise

The International Panel on Climate Change (IPCC) estimates that global average sea level will rise between 0.6 and 2 feet (0.18 to 0.59 meters) in the next century. In the last century, relative sea level rose 5 to 6 inches more than the global average along the Gulf Coast because these coastal lands are subsiding (IPCC, 2007). Many coastal engineering manuals are now calling for

design considerations for sea level rise. The uncertainty in relative and eustatic sea level rise and land subsidence provides many design constraints for traditional breakwater structures. Many structures require repair and maintenance, or may even lack an overall effectiveness to serve as a breakwater structure.

Biologically dominated engineered oyster reefs are three-dimensional structures that can accommodate changes in relative sea level rise and subsidence because the biological component is capable of adapting to environmental conditions. These structures are a novel and significant method of coastal restoration and protection. Increased monitoring and surveying are necessary to document the immediate and long-term environmental and ecological benefits, as well as their overall effectiveness, as sustainable breakwater structures.

1.7 Land Subsidence

Scientists expect sea level to rise 1 to 2 feet globally by the year 2100, though these estimates could increase if grounded ice in Greenland and Antarctica melts more quickly than expected (IPCC, 2007). But global sea level rise has historically contributed only about 10% of observed “relative” sea level rise in coastal Louisiana. The difference is a consequence of the contribution of subsidence, which is the sinking of land in a process that varies throughout the coast plain. Generally, these regional processes have greater effect closer to the seaward margin, but human activities like withdrawing subsurface fluids during oil and gas production, and depressurizing shallow gas fields have also greatly enhanced local subsidence (Blum and Roberts, 2009).

Climate change, sea level rise, and subsidence contribute to a type of land loss that may not be effectively managed by a traditional detached breakwater system. Subsidence, which refers to “the loss of surface elevation due to removal of subsurface support,” is caused by crustal

deformation; sediment compaction; withdrawal of groundwater, hydrocarbons, geothermal fluids or minerals (sulphur); and dewatering of organic soils (NRC, 1991). Alternatively, regional subsidence could be the result of south Louisiana slowly sliding into the deeper waters of the Gulf of Mexico, a process several orders of magnitude greater than the offshore slumps that threaten pipelines and drilling platforms (Gowen et al., 2004). Subsidence impacts the effectiveness of breakwater structures because the design height sinks in the water column over time. Along with sea level rise and structure settlement, the breakwater can become ineffective or require significant modifications, rendering the project economically unfeasible.

1.8 Sediment Management

Sediment management is an important concept related to coastal erosion because lack of system sediment supply inhibits the natural ability of the coastal zone to replenish land over time. The concept of Regional Sediment Management (RSM) derived from the U.S. Army Corps of Engineers (ACOE) in the early 1990s is related to conservation and management of sediments in the littoral zone and attempting to “design with nature,” by utilizing an understanding of sediment movement in a region and the interrelationships of projects and management actions for ecosystem restoration and protection (Martin, 2002). In Louisiana, more than a century of Mississippi River flood control has diminished the sediment supply available to replenish the coastal lands that provide habitat and shelter the coast from storm events.

Freshwater and sediment diversions are part of the state’s 2012 Master Plan to restore Louisiana’s coastal zone to create marshland and re-establish oyster seed grounds. River diversions provide a man-made hydraulic connection to allow flow from the river to new areas of existing wetlands and marshland. Freshwater river diversions will re-introduce sediment supply

to marshlands and provide nutrients and nourishment to wetlands. Over time, diversions are expected to increase a natural land building capacity within the coastal zone. Large diversions and a series of small diversions are currently being evaluated to determine the most effective method to ensure optimal recovery of the wetland and marshes that serve as natural buffers to attenuate wave energy from hurricanes and other storms. Hurricanes can also influence system sediment distribution by naturally moving sediment to low-energy zones, which in some cases can actually bury existing low-profile oyster reefs otherwise referred to as two-dimensional reefs. High-relief three-dimensional oyster reefs are less susceptible to this sediment deposition and remain functional. However, extreme hurricane events can scour and bury high-profile oyster reefs, as well as expose previously buried reefs.

1.9 Hurricanes

During the past decade, the U.S. Gulf of Mexico coast has been subjected to the landfall of 11 hurricanes, and an additional five hurricanes made landfall along the U.S. Atlantic coast (Steyer, 2010). The U.S. Geological Survey, along with the National Aeronautics and Space Administration and the U.S. Army Corps of Engineers, flew airborne lidar surveys before and after landfall of most of these storms to detect the magnitudes of coastal change resulting from waves and storm surge (e.g. Sallenger, et al. 2006; Doran et al., 2009; Steyer, 2010). Each of the hurricanes caused significant changes to land mass. Extreme storms can cause permanent changes to the coast. In the absence of nourishing processes like natural riverine sediment supply, coasts may or may not recover over prolonged time scales (Sallenger, 1992).

Approximately 80 tropical storms or hurricanes have made landfall on or near the Louisiana coast since 1899 (NOAA, 2008). Of these, 14 have been severe storms – rated Category 3 or

higher on the Saffir-Simpson scale (NOAA, 2008). Thus, a severe hurricane of Category 3 or higher comes ashore on the Louisiana coast every seven or eight years, on average. Cameron and Vermilion parishes in southwest Louisiana, and Plaquemines and St. Bernard parishes in southeast Louisiana, have the highest potential for hurricane landfall (Simpson and Riehl, 1981). The ability of biologically dominated, artificial reefs serving as breakwaters to dissipate wave energy, reduce storm surge, and provide shoreline protection within the coastal zone is reason enough to justify building them.

With rapid sea level rise anticipated over the next century, storm-induced coastal erosion may increase, even if hurricane intensity and frequency remain the same. Extreme storms, sea level rise, and reduced sediment supply all play roles in the degradation and ultimate disappearance of barrier islands. Louisiana barrier islands may be reasonable analogs for what may happen to U.S. east coast barrier islands over the next 100 years (Sallenger, 2006).

1.10 Summary

Louisiana's coast has been experiencing rapid land loss and is losing coastal wetlands at a rate of 65-90 square kilometers per year (Coast 2050). The average short-term rate of shoreline erosion is 9.4 m/yr, up from a long-term average of 6.1 m/yr (Penland et al., 2005). Rapid subsidence, eustatic sea level rise, channelization in marshes, and drastic alteration to the Mississippi River's natural building processes are the main reasons for this accelerated land loss (Hatton et al., 1983). Storm events, such as the hurricanes of 2005, create high-energy waves and wash-over events that breach beaches and barrier islands. These features recover during fair weather conditions, but not to their original conditions (Penland et al., 2005). The loss of land mass can be attributed to the lack of riverine sediment input, to land subsidence, sea level rise, altered

hydrology from canal construction and other anthropological action, and erosion (Day et al., 2007). This loss provides the impetus for environmentally and economically sustainable coastal engineering and management solutions to protect and restore the Louisiana coastal zone.

Eastern oysters (*Crassostrea virginica*) can biologically dominate artificial reef structures used in the Gulf of Mexico as nearshore intertidal coastal breakwaters. The biological growth over time can increase the structures' strength and increase breakwater effects to dampen wave energy and promote shoreline protection. These reefs can also serve as oyster broodstock sanctuaries, providing a nexus to the public oyster grounds that benefits the aquaculture industry. The use of biologically dominated, detached, breakwaters may provide a viable solution to coastal protection while offering multiple ecosystem benefits. Limitations do exist—optimal environmental conditions must exist within the intertidal zone to sustain the oysters, and proper seasonal emplacements are necessary to minimize biofouling and maximize oyster larvae settlement. Finally, extreme weather events may dislodge the structures and/or cause excessive siltation covering the structure.

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CHAPTER 2: BIOMETRICS ON EXPERIMENTAL THREE-DIMENSIONAL HIGH-RELIEF ARTIFICIAL OYSTER BREAKWATER REEFS IN THE GULF OF MEXICO

An experimental study was conducted at Rockefeller Wildlife Refuge monitoring oyster biometrics on high-relief three-dimensional artificial reefs using concrete scaffoldings for growth substrates. Spat plates were used to measure spatfall intensity; fouling plates were used to monitor the biofouling communities; and oyster biometrics were observed and recorded. Concrete substrate material was also analyzed for biological domination and material flexural strength. Spat plate data indicated the spring spatfall exceeded 10,000 spat/m² in some locations. Oyster shell height measurements of 50 cm were recorded after six months of growth, with oyster counts exceeding 500 per m² on the artificial concrete modular breakwater reefs. These biologically dominated concrete structures showed a significant increase in flexural strength over time from an initial 28-day peak curing load of 100 lbs to peak loads of 479 lbs in six months and 1,344 lbs in two years. The use of biologically dominated concrete structures appears to be a viable coastal protection method in the Gulf of Mexico and provides multiple benefits to ecosystem services.

2.1 Introduction

Oysters are ecosystem engineers that produce reef habitat (Beck, 2011). Ecosystem engineering species make many contributions to ecosystem services (Brumbaugh and Coen, 2009). Oysters provide habitat for marine life; filtration to improve water quality; carbon sequestration; and they form intertidal reefs that can reduce wave energy, trap sediment, and mitigate land loss.

Oysters were once valued primarily as a fishery resource, but today increasing attention is being focused on other ecosystem services that oysters and their reefs provide in coastal bays and

estuaries (Brumbaugh and Coen, 2009). Inshore hard-bottom substrate (including oyster reefs) is important to estuarine fish communities in the Gulf of Mexico. Habitat loss, disease, overharvest, and the failure to replace shell have severely decreased the amount of high-relief oyster reefs available to finfish (Simonsen, 2007). The decline in these high-relief oyster reefs has also left the coastline vulnerable to increased wave energy and erosion caused by channelization in the marsh by the oil industry (permitted by state and federal agencies), leveeing of the Mississippi River, land subsidence, saltwater intrusion, and sea level rise, all of which have ecological implications within the coastal environment.

Biologically dominated engineered reef technologies can dissipate wave energy and allow sediment accumulation, while protecting shorelines. These reefs facilitate ecological environments and provide substrate for oyster growth (Hall, 2009). Oyster growth on these artificial reefs reinforces their structural integrity as a breakwater, increasing wave energy dissipation and shoreline protection, as well as offsetting land subsidence and structure settlement (Hall, 2011). Biologically dominated engineered reef technologies are relatively simple in their conception; however, additional research is warranted to further quantify oyster biometrics on artificial concrete reefs.

2.2 Background

Oysters have been described as a keystone species within their habitats, and they provide a number of valuable functions in intricate communities of species, such as water filtration, recycling biological material, capturing primary productivity, processing phytoplankton, boosting benthic productivity, and providing feeding and nesting habitat for numerous other species (LDWF, 2004). Oysters serve to improve water quality by consuming phytoplankton

and storing nutrients as biomass, depositing the nutrients to the benthos, and creating high-quality protein (gametes) for other filter feeders (NCDMF, 2001; Newell et al., 2004). This process leads to reduced aquatic turbidity and nutrient load, while there is also an increase in dissolved oxygen, which may result in an increased stimulation of submerged aquatic vegetation (Newell et al., 2004; Cerco et al., 2005). Since oyster reefs provide a habitat for other species, they make an area attractive to both the commercial and recreational fishing industries (NCDMF, 2001; LDWF, 2004; Street et al., 2005).

2.3 Oyster Biology

Physical properties are important characteristics of any organism used by engineers, and biologists are interested in growth characteristics of eastern oysters (*Crassostrea virginica*). (Wheaton, 2007). These physical properties allow engineers to incorporate biology into design scenarios by utilizing natural systems. Oysters are one species that allow engineers the ability to design with nature. Oysters have the ability to colonize and change sexes. They reproduce, creating larvae in large numbers that seek and settle on hard surface substrates. Oyster larvae need hard substrates to attach and become spat. Concrete makes ideal scaffolding for oyster growth. Temperature and salinity seem to be the most important factors triggering oyster reproduction, which typically occurs through the spring and fall. Larvae settle or spat onto substrates and begin to grow, filtering water for nutrients. As oysters grow, they cement themselves together and the reef develops in three dimensions.

A variety of physical factors affects setting, including water temperature, salinity, and light, as well as biochemical cues from other oysters. Larvae are negatively phototactic and tend to settle in shaded areas and have been shown to prefer highly irregular or pitted surfaces. Due to the

oysters' colonial nature, larval oysters usually select a surface near other oysters to settle, most likely due to waterborne pheromones (Kennedy, 1996 and Anderson, 1995). Biofilms stimulate setting of oyster larvae caused by chemical messengers such as L-3-4-dihydroxyphenylalanine (L-Dopa or dopamine) and melanin that bacteria produce and ammonia (NH₃) (Kennedy, 1996). An oyster life cycle is depicted below in Figure 2.1, showing trochophore larval development to post-larval spat-setting in approximately 14 days, depending on water temperature.

Oysters compete for space with other benthic organisms such as bryozoans, barnacles, hooked mussels, slipper shells, anemones, serpulid worms, tunicates and algae (Berrigan, 1991). The impact of competition for settlement space in the Gulf of Mexico has not been completely determined, and in some instances these species have a purely commensal relationship with oysters (Berrigan, 1991).

Oyster mortality frequently occurs from predation (e.g., the oyster drill, *Strominata haemastoma*) and disease (*Perkinsus marinus*). Despite predation and disease, oysters can typically thrive in a vast range of salinities and temperatures, surviving best in moderate salinities (10-25 ppt) and moderate temperatures (10-35° C). The ability of an oyster to survive a considerable range of environmental conditions makes it an ideal keystone species, supporting entire ecosystems.

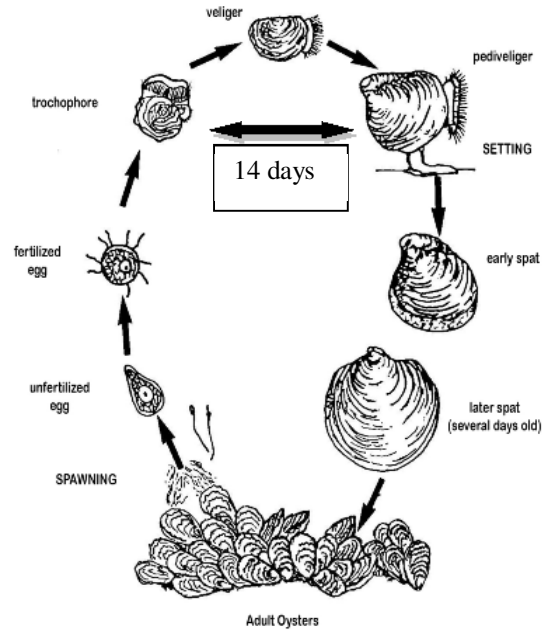


Figure 2.1: Oyster life cycle (after Berrigan et. al, 1991)

2.3.1 Environmental Conditions

The most important factor influencing the distribution and abundance of oysters is probably salinity (Berrigan, 1991), as oyster reef populations thrive in only a small range of salinities. When salinity is less than 10 ppt in the spring and summer, spawning is inhibited, and larval survival is reduced; whereas where salinities greater than 15 ppt predominate, mature larvae are abundant, but survival of recently set oysters is poor because of increased numbers of fouling organisms and predators (Berrigan, 1991). The effects of salinity variation on oyster populations depend largely on the range of the fluctuations and the rate of change. Salinity also affects the timing and intensity of spat setting, as do temperature and other factors. Setting intensity in Louisiana is consistently high when salinities range from 16-22 ppt, with a peak occurring between 20-22 ppt (Chatry et al., 1983).

2.4 Oyster Reefs

Shellfish act as a natural coastal buffer to absorb wave energy directed at shorelines. With this ability, they reduce erosion caused by boat wakes, sea level rise, and storms (Meyer, 1997 and Piazza et al., 2005). In addition, shellfish reefs play an important role as habitat for other species; fishes produced on oyster reefs have significant value to coastal economies (Grabowski and Peterson 2007). As oyster colonies grow, they form reefs that can reduce wave energy and protect coastal lands from erosion. Providing a high-relief, three-dimensional scaffolding for growth enhances the oyster reef's ability to function as a coastal breakwater.

Oysters are colonial and grow their shells, forming reefs, by a cementing calcification process within each oyster. Oyster shells are made of calcium carbonate, which is filtered from the water and formed into the outer shell once secreted by the mantle (Mount et. al., 2004). Oyster reefs may be found along both the Pacific and Atlantic coasts and in the Gulf of Mexico. They have the ability to survive in cold, brackish waters such as lagoons, bays, and estuaries (Kilgen, 1989). Oysters are resistant to waves, and as the sea level rises, they can adapt to some of these changes (Hall, 2009). Oyster reef maximum elevation is related to the minimum time of inundation in the middle range of the intertidal zone (CEM, 2006). People should view oyster reefs as both a significant habitat and environment and make these reefs a priority for habitat management and conservation. It is said that oyster fisheries in the Gulf of Mexico are probably the last remaining opportunity to achieve both large-scale oyster reef conservation and sustainable fisheries (Beck, 2011).

2.5 Bioengineered Artificial Oyster Reefs

Figure 2.5.1 shows a cross section of a cylindrical concrete modular unit with two years of oyster growth at an existing pilot reef study site located in Rockefeller Wildlife Refuge in Louisiana.

These artificial ring structures are generally considered biologically dominated when the biomass accrued in mass or volume exceeds that of the original structural framework. Oysters biologically dominate these engineered coastal breakwaters as seen from the cross sectional area below. Dehon (2010) suggested a nonlinear growth pattern with possibly exponential growth, at least for the two-year period of his study, and noted the associated carbon sequestration potential of the reefs. Additional monitoring of these existing reefs and newer reefs was conducted to determine oyster biometrics on artificial reef structures.



Figure 2.2 a, b: (a) Cross section of concrete oyster reef ring (2009), from (b) existing biologically dominated ring reef.

A study by Swann (2008) showed oyster density on the coastal breakwater reefs measured 19 months post-installation was 205 oysters/m². Measurements behind the breakwater also indicated sediment accretion. The dual function of these structures has controlled the erosion

behind the breakwater and has provided habitat for a wide array of species, including spotted sea trout (*Cynoscion nebulosus*), blue crabs (*Callinectes sapidus*), Gulf stone crabs (*Menippe adina*), eastern oyster (*Crassostrea virginica*), red drum (*Sciaenops ocellatus*), southern flounder (*Paralichthys lethostigma*), and various species of commercially important shrimp such as brown shrimp (*Farfantepenaeus aztecus*), pink shrimp (*F. duorarum*), and white shrimp (*Litopenaeus setiferus*) (Swann, 2008). The structure also provides habitat for biofouling organisms that may actually decrease the amount of oysters on these reefs but add to overall system biodiversity.

2.5.1 Biofouling

Nelson et al. (1994) state, “the fouling community, consisting of those organisms which attach to hard structures, is an important component of the total biological assemblage that develops on newly established artificial reefs”. Fouling organisms provide an important food source for a variety of the fish species that recruit to artificial reefs, and they may, over time, provide additional structural elements to the reef (Bailey-Brock, 1989; Vose, 1990). Initial recruitment of fouling organisms can occur rapidly, with colonization of barnacles covering up to 60-70% of brick surfaces within the first month of reef placement (Nelson et al., 1994).

Figure 2.3 below shows the potential for biofouling captured on tile spat plates used at the pilot research reefs and shows the presence of oyster spat, barnacles, and bryozoans competing for space. Installing artificial reefs outside times of peak spatfall can lead to excessive biofouling. Biological responses of the fouling community might be reflected in differences in the settlement rates of initial colonizers of the reef (Fitzhardinge and Bailey-Brock, 1989), in alteration of community composition over time, and/or in differences in the mortality of settled organisms (Nelson et al., 1994).

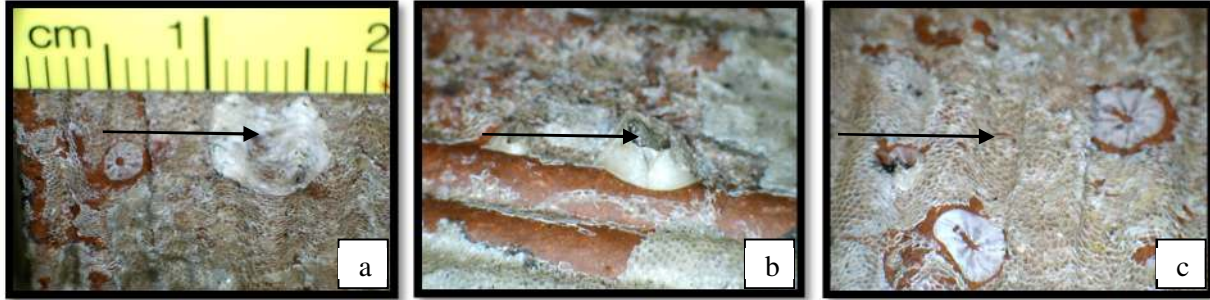


Figure 2.3 a-c: Biofouling plate with visible (a) spat, (b) barnacles, and (c) bryozoans.

Studies have hinted at paradigms involving the biological fouling of natural and artificial structures (Brown and Swearingem, 1998; Bartol et al., 1997; Delort et al., 2000; Dittman et al., 1998), and it is imperative that accurate descriptions of biological attachment and survival are utilized in the design of biologically dominated structures. Proper seasonal placement and location within the intertidal zone are two important aspects to optimize the design of biologically dominated artificial oyster reefs used as breakwaters for coastal restoration and protection.

2.6 Materials and Methods

Concrete modular units were emplaced as detached intertidal breakwater reefs during the spring of 2011 at Rockefeller Wildlife Refuge [29° 40' 11.21" N; 92° 45' 46.29" W] to initiate the pilot study. Several configurations were installed, along with rectangular concrete logs for lab analysis of oyster growth and material strength. Spat plates were also used to determine spatfall estimates. Concrete cultch plates were placed within the ring structures to further analyze biological activity on alternate aggregate substrates. Oyster biometrics were monitored and used to determine growth, size, and spatial distribution within the water column.

2.6.1 Spat Plates

Spat plates were made from 10.2 cm² (4 x 4 inch) hardy board, and biofouling plates of terracotta tiles measured 15.2 cm² (6 x 6 inch). These tiles were placed horizontally in triplicate, separated by 1.3 cm (1/2 inch) PVC spacers and were suspended in the water column by PVC pipes anchored to the seafloor. Spat plates were monitored bi-weekly during the presumed spatfall and monthly thereafter for biofouling assessments. Spat plate configurations and monitoring techniques are depicted in Figure 2.4.



Figure 2.4 a, b, c: (a) Spat plate configuration (b) Veho™ digital microscope imagery, and (c) dissecting microscope lab set-up (Risinger, 2011).

The spat plates were analyzed with a dissecting microscope and Veho™ digital microscope. The tiles were marked with a grid pattern for analysis, and each individual spat was counted and recorded. Bryozoans and barnacles were also observed, and estimated coverage was determined.

2.6.2 Oyster Cultch and Concrete Substrates

Sessile bivalves attach and grow on a substrate termed “cultch”. In a natural environment, oyster or clam shells provide a suitable substrate for larval attachment. Alternative cultch materials exist and have been more common given the dwindling supply of natural materials. Cultchless

material has also been explored, using gypsum rock that dissolves over time (Soniati, 1991; Haywood, 1992; Soniat, 2005). Limestone rock and crushed concrete materials have also been used to reestablish oyster reefs on public seed grounds and to promote the aquaculture industry. These low-relief, low-profile, two-dimensional reefs can be effective for oyster growth in the short term, but may not be sustainable over time, as they can become buried in sediment after storm events. Typically these types of reefs are replenished with cultch annually as part of commercial fisheries efforts.

For this study, cultch plates were used to monitor oyster settlement and growth within the ring structures. Cultch plates were made during concrete pours by placing the lid of a plastic bucket within the ring form to capture excess concrete. They were comprised of aggregate mixtures that matched the ring composition. The cultch plates were placed inside the deployed ring structures and used to visually monitor spat settlement and oyster recruitment as illustrated later in Figure 2.7. These circular disks were removed and taken back to the lab for analysis.

2.6.3 Oyster Biometrics

Oyster biometrics were monitored on the concrete artificial reef scaffolds to determine the extent of biological domination over time. Biometrics included the number of spat settled, oyster size, and spat and oyster spatial distribution among the artificial reefs. Oyster mortality was observed on some ring structures, but is not quantified herein as part of the experimental results. Oyster tally sheets were recorded monthly for each monitoring session using random ring counts. Individual oyster height measurements were taken from varied depths in the water column, and oyster weights were measured in a laboratory setting using mollusks collected from the supplemental detachable concrete “log” emplacements.

2.7 Results

2.7.1 Spat Recruitment Plates and Oyster Larval Settlement

Spat plate counts are summarized in Figure 2.5. The results indicate a spatfall in May 2011. No spatfall was observed using spat plates for the fall of 2011; however, spat growth was observed on concrete modular units in late December 2011. A late seasonal spat set is indicated by the observations. Spatfall distribution within the water column indicates a higher spat set on the center tiles. A higher spat set was also observed closer to the existing concrete oyster reefs, perhaps indicating the location as a broodstock reef.

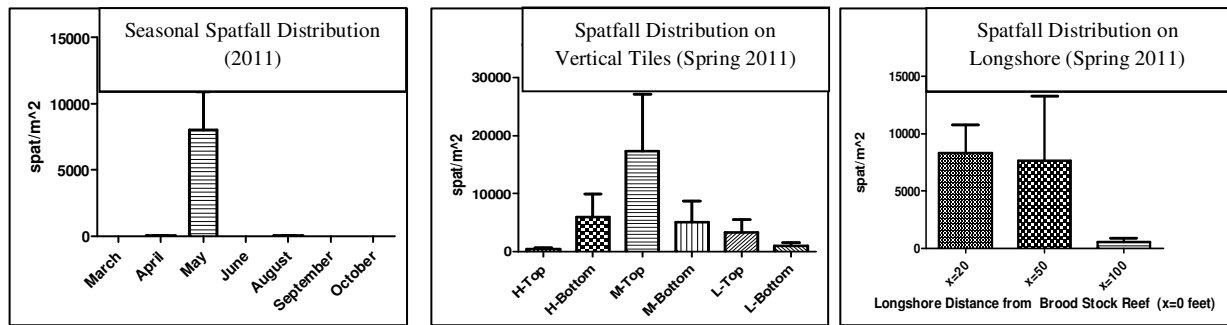


Figure 2.5 a-c: (a) 2011 seasonal spat counts, (b) Spring 2011 vertical tile spatfall distribution, and (c) Spring 2011 long-shore spatfall distribution from broodstock reef

Fewer than 50 spat/m² were observed on spat plates during the months of April and August, and no observable spat were detected thereafter, with the exception of the peak spat set observed in May: however, spat were observed on the concrete reef structures as late as December. The peak spat set was observed in May 2011, with over 10,000 spat/m² measured on some plates. The top section of the middle spat plate recorded the highest spat count with over 20,000 spat/m². Spat plates were also placed at varied distances (e.g., 20, 50, and 100 ft) from an

existing biologically dominated “broodstock” reef. Spat plates placed within 50 feet of this existing broodstock reef experienced the highest oyster settlement, averaging 8,500 spat/m².

Water quality parameters during the spat season were taken from a U.S. Geological Survey (USGS) station and reviewed for temperature and salinity fluctuations and presented below. The results show the water quality parameters during the recorded spatfall. Temperature and salinity spikes were observed during spatfall on May 21, perhaps inducing the reproductive cycle. Spat plates collected and analyzed on May 31 confirmed that the spring spat cycle occurred.

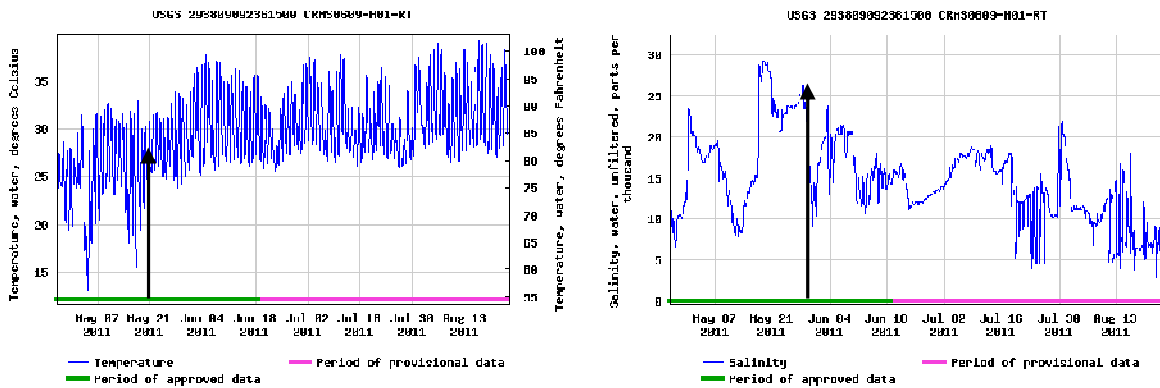


Figure 2.6 a, b: (a) USGS temperature data near Rockefeller Refuge and (b) USGS salinity variations.

Optimal seasonal emplacements of biologically dominated breakwaters should occur in the spring prior to peak spatfall to allow adequate oyster larvae settlement and to minimize biofouling on the structures.

2.7.2 Oyster Cultch Plates

Figure 2.7, below, shows a lava rock aggregate cultch plate with nearly 100% oyster recruitment, while the other image shows an alternate cultch plate used inside the rings.



Figure 2.7 a, b: (a) Lava rock cultch plate and (b) circular honey-comb cultch plate.

2.7.3 Oyster Biometrics on Artificial Reefs

Oyster biometrics were monitored on the existing concrete modular units as seen below. The random ring count is illustrated in Figure 2.8. This technique was used for oyster counts on all ring emplacements. Random circular oyster counts on artificial reef emplacements exceeded 150 oysters/m² in most locations, with some counts nearing 500 oysters/m². The concrete modular units have a surface area of 0.78 m² each (1,210 in²); therefore, oyster recruitment measured up to 400 oysters on some rings.



Figure 2.8 a, b: (a) Oyster mortality on artificial concrete ring, and (b) mortality after two months growth and removal from intertidal zone.

Oyster height exceeded 50 mm on the artificial reefs during the six-month observation period. Greater growth was observed in the medium and lower water column of the intertidal zone when compared to the upper intertidal zone ($P=0.0096$), which was also indicated by individual oyster weights ($P = .1558$). Oyster growth was observed monthly on all reef emplacements, and oyster height measurements were recorded in different zones of the water column, as well as oyster weight.

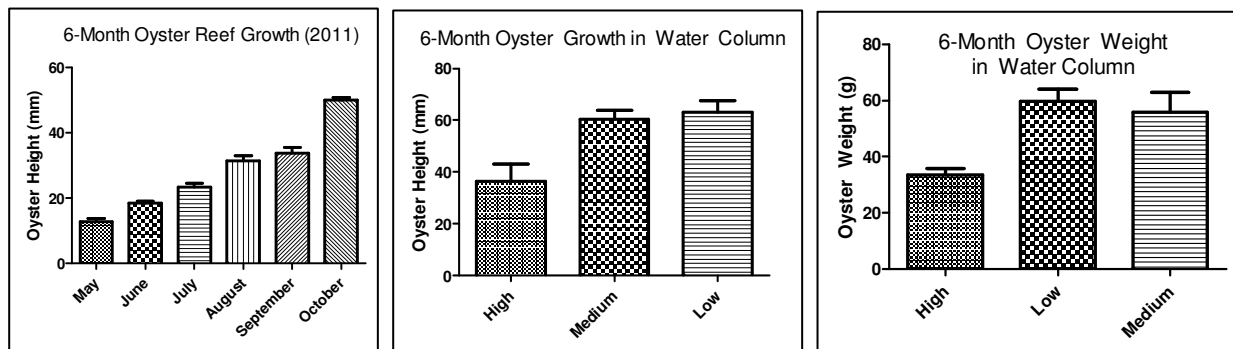


Figure 2.9 a, b, c: (a) 6-month oyster heights by month (in mm) showing no significant differences in August/September (ANOVA, $P < 0.05$) (b) 6-month Oyster heights (in mm) by water column depth showing no significant differences in medium/low locations (ANOVA, $P < 0.05$), and (c) 6-month oyster weights (in g) by water column depth showing no significant differences in medium/low locations (ANOVA, $P < 0.05$).

These results, presented in Figure 2.9, indicate statistically significant growth on all rings, with exception to the months of August and September. No statistically significant oyster height measurements occurred within the medium and lower zone of the concrete ring cylinders.

2.7.4 Biofouling

Biofouling was observed on concrete rings placed in the lower intertidal zone as seen in Figure 2.10. Algae growth was observed that appeared to overtake the concrete structure and preclude future oyster settlement. These observations were further enforced on spat plates that remained in the water for longer than 30 days after the spat cycle had ended.



Figure 2.10 a, b: (a) Biofouling on ring in lower intertidal zone (b) Biofouling on ring in upper intertidal zone emplaced during summer months (Risinger, 2011).

2.7.5 Biological Growth and Concrete Strength Analysis

Figure 2.11 below summarizes structural flexural load relationships among three different oyster growth durations on concrete material taken from pilot reefs within the study area. Significant increases in flexural strength were exhibited over time, in part due to oyster growth on the concrete bar structure.

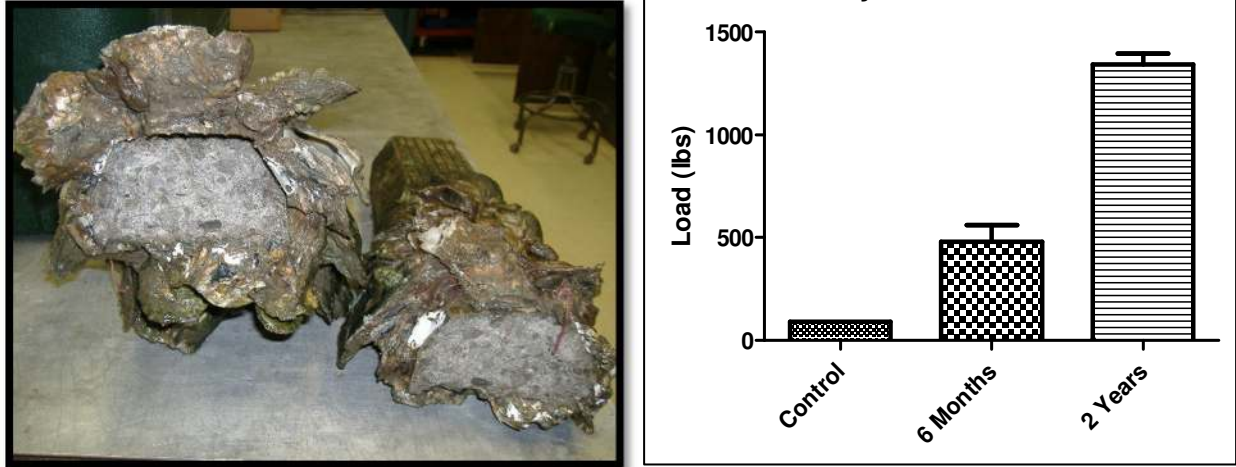


Figure 2.11 a, b: (a) Concrete with oyster growth and (b) Flexural strength variations.

2.8 Discussion and Conclusion

Emplacing concrete structures as submerged intertidal breakwaters to attract oyster settlement can have an immediate influence on leeward sediment settlement rates on shorelines, as well as facilitate other ecosystem services and restoration and recovery efforts. Oyster growth after six months on these structures up to and exceeded 50 cm after initial spat settlement rates as high as 10,000 spat/m². Oyster counts on these structures after six months exceeded 500 oysters per m². Further, the structural integrity of the engineered structure increased as the oysters cemented themselves together, as indicated by the flexural peak force loading analysis results of 479 lbs in six months and 1,344 lbs in two years. Although these three-dimensional breakwater oyster reefs are typically not harvestable, they become oyster broodstock sanctuaries, producing billions of larvae each year that could populate nearby public seed grounds for harvest.

Cultch plates provided a good visual representation of the amount of oyster settlement and survival and biofouling within the different composite aggregate ring structures. Typically, the aggregate with more rugosity and porosity experienced the most settlement and survival. Less

biofouling was observed on cultch plates that were placed in the spring and fall seasons. The biofouling also seemed to increase and oyster recruitment decreased if installation occurred later in the summer season.

The observed results indicate optimal seasonal placement of rings should be in the spring or fall, several weeks prior to presumed spatfall in order to preclude significant biofouling and to maximize oyster spat settlement. The location of placement within the intertidal zone is also of significance to oyster recruitment and spat settlement when competing with other organisms. If the rings are placed in the marine environment with significant time for biofouling to occur, reduced oyster spat settlement may result.

Additional factors that may increase structure strength over time in a marine environment include the potential for varied concrete mixtures among reefs and normal hardening over time. These factors were not able to be quantified in this study, so only a general conclusion can be drawn from the data indicating that oyster growth increases composite material flexural strength over time. Log samples from biologically dominated concrete structures showed a significant increase in flexural strength over time from an initial 28-day peak curing load of 100 lbs to peak loads of 479 lbs in six months and 1,344 lbs in two years. This significant increase in strength is likely due, in part, to the biological oyster growth (calcification) over time that encapsulates the concrete.

2.9 Summary and Future Work

The oyster is a keystone species and an ecosystem engineer, needing only a scaffold or substrate upon which to settle and survive in most coastal zones. They are sessile, colonial, and fecund bivalves producing millions of offspring each year that settle upon existing oyster shells (or other

suitable substrates) to form reefs. They provide many ecosystem services, including habitat and food for other aquatic organisms, water filtration, and carbon biosequestration capabilities.

Artificial reefs can also dissipate wave energy, promoting sediment accretion and mitigating coastal land loss from hurricanes, with increasing benefits attained when becoming biologically-dominated by oyster growth.

Oysters naturally form high-relief, three-dimensional reefs over time, but a significant decline in these historic reefs has led to more recent two-dimensional low-relief reefs in public seed grounds facilitated by cultch deposits for aquaculture harvest. Clam shells, oyster shells, limestone rock, and concrete have been used as cultch to facilitate oyster recovery in public seed grounds. The resulting low-profile reefs are less sustainable and can become silted over several years. High-profile, three-dimensional artificial oyster reefs used as intertidal breakwaters may also be limited by this effect if subjected to extreme weather conditions (i.e., hurricanes).

Optimal seasonal placement of these structures is recommended to facilitate oyster larvae settlement and to reduce biofouling effects.

The use of artificial concrete substrates as scaffoldings for oyster recruitment and growth was researched in the intertidal region of the Louisiana State Rockefeller Wildlife Refuge to determine biological domination. The results of this experimental study show the benefit of artificial oyster reefs serving as broodstock reefs and ecological habitats on artificial concrete module scaffoldings as it relates to sustainable coastal protection and restoration efforts. The additional monitoring of both oysters biologically dominating artificial oyster reefs and the reefs serving as shoreline coastal protection and restoration is paramount to quantify the long-term benefits of these technologies to coastal Louisiana. Finally, a nexus can be made between these reefs and intrinsic benefits to the public oyster seed grounds of Louisiana.

Water quality parameters and additional oyster biometrics should be the focus of future research. This relates to temperature and salinity fluctuations experienced by oyster broodstocks during breeding cycles and improving artificial scaffolds to facilitate oyster settlement and growth. As newer coastal restoration methods are explored, fluctuations in water quality parameters are uncertain in the Gulf of Mexico. Large- and small-scale freshwater diversions introduced into the system may have significant impacts on oyster life cycles by altering temperature and salinity regimes. The biological and ecological responses of oyster to diversions may need to be mitigated in select locations stable enough to facilitate biological growth on artificial scaffolds such as bioengineered oyster reefs. Finally, long-term demonstration studies of scale are currently underway and should continue to be monitored to further evaluate the effectiveness of these technologies.

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CHAPTER 3: BIOLOGICALLY DOMINATED ENGINEERED COASTAL BREAKWATER SYSTEMS UTILIZING ALTERNATIVE LIGHTWEIGHT AGGREGATES

Research was conducted on a low-energy, pilot scale breakwater experiment site at Rockefeller Wildlife Refuge using cylindrical, concrete modular units to evaluate the use of biologically dominated reef technologies as engineered breakwater structures using lightweight aggregates. Pilot scale concrete modular ring units were manufactured for the purpose of evaluating material strength in theoretical, laboratory, and field conditions. Alternate geometrical configurations were explored (i.e., light, medium, and heavy emplacements) and compared to traditional rock breakwaters. In some cases, these units were less than 10% by weight total mass of traditional structures. Lightweight aggregates (i.e., vitrified expanded clay) showed optimal strength and weight ratios when compared to traditional aggregates weighing less than 50% by volume with no statistically significant difference in ASTM-39 Compressive (peak load) Strength (3,328 lbs with $P < .001$). Biologically dominated concrete structures showed a significant increase in ASTM-78 Flexural Strength from an initial 28-day peak curing load of 100 lbs to peak loads of 479 lbs in six months and 1,344 lbs in two years. These results indicate that a relatively weak initial structure can become stronger over time as it becomes biologically dominated.

3.1 Introduction

Coastal breakwaters, reefs, and wetlands all moderate wave energy and coastal sediment transport processes to facilitate shoreline protection. A great challenge of coastal engineering is creating a proper design for these structures, along with developing monitoring strategies to quantify long-term effectiveness. Technologies such as artificial breakwater reef structures are also being investigated in field experiments (CEM, 2006). Bioengineered artificial reefs become

biologically dominated by calcifying oyster growth, which increases the structures' overall effectiveness to serve as a breakwater system. As oysters grow on the circular concrete modular units, wave energy is attenuated and sediment accumulates on the leeward side of the structure, allowing shoreline stabilization to occur.

3.2 Background

Concrete consists of aggregates such as sand or stone bound together in a cement matrix. Two main types of concretes are air-set cements and hydraulic cements (Ortego, 2009). Air-set cements harden through drying. Hydraulic cements harden due to hydration, and the most used of this type is Portland cement. Portland cement is created by combining limestone or chalk, gypsum, kaolin, shale, or sand and various types of slag. The materials are burned to form a fused mass and ground into the cement powder (Mitchell 2004). The primary components of Portland cement are tricalcium silicate ($3\text{CaO}\cdot\text{SiO}_2$), dicalcium silicate ($2\text{CaO}\cdot\text{SiO}_2$), tricalcium aluminate ($3\text{CaO}\cdot\text{Al}_2\text{O}_3$), and tetracalcium aluminoferrite ($4\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot\text{Fe}_2\text{O}_3$) (Mitchell, 2004). The strengthening of Portland cement is due primarily to the creation of dicalcium silicate hydrate ($2\text{CaO}\cdot\text{SiO}_2\cdot x\text{H}_2\text{O}$), as well as some calcium hydroxide salts (Mitchell, 2004). Portland cement is non-toxic and allows the colonization of marine organisms.

Once Portland cement concretes are exposed to seawater, their physical properties can be altered (Ortego, et al., 2006; Bai et al., 2003). The processes of seawater affecting concrete include: wetting and drying cycles, leaching, temperature variations, corrosion of reinforcing steel, battering by waves and tides, sulfate attack, and freeze/thaw cycles (Washa, 1998). However, Mohammed et al. (2004) found that after 20 years in a tidal environment, concrete made from ordinary Portland cement showed no significant decrease in strength. Oyster growth on these

concrete structures may also prove to increase overall strength. Previous work (Hall, 2009) has shown that by providing lightweight, three-dimensional cylindrical concrete structures, the growth of oysters (*Crassostrea virginica*) and other species can be encouraged at a number of field sites in the Gulf of Mexico.

3.3 Coastal Breakwater Systems

Breakwaters are typically constructed from rock, cement armor stones, sunken barges or ships, or any heavy objects that break up wave action (CCEZM, 1990). Nearshore breakwaters are segmented in the intertidal zone and detached from the shoreline; thus, they provide optimal protection while allowing water (as well as sediment and organisms in the water) to pass through. These barriers provide a sheltered area, which serves as a reservoir for sediments carried by the diffracted waves (Benassai, 2006). These provide a similar effect as a sediment fence, which is used to promote sedimentation (Scarton et al., 2000 and Boumans et al., 1997). As sediment builds up over time, the breakwaters create salients and sometimes tombolos as the shore connects to the breakwater (Chen, 2008). The use of offshore breakwaters as a means of beach protection and passive beach nourishment has increased more quickly than groin-type structures in the last decades. This shows a strong trend toward the use of breakwaters over groins as a means of beach protection and stabilization (Benassai, 2006). However, traditional breakwaters do not maximize the biological benefits of an artificial reef.

It has also been suggested that oyster reefs should be used as a method of coastal restoration in a Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA) project (Foret, 2003; LDNR, 2004). The functional design of artificial reef systems for shore protection is a relatively new area of coastal engineering; therefore, no general design rules exist (CEM, 2006). Several

demonstration projects in Louisiana and the Gulf Coast utilize these technologies for coastal protection and restoration efforts. Each project is designed specifically to accomplish project objectives (e.g., habitat enhancement or wave energy reduction) and engineered to satisfy existing site conditions. As the bioengineered oyster reef is in its infancy, coastal engineers and scientists should continue to closely monitor these technologies to evaluate long-term sustainability of biologically dominated structures.

The use of artificial cylindrical concrete reefs comprised of lightweight aggregate structures may prove to be an optimal approach to coastal protection and shoreline stabilization in the Gulf of Mexico. Lightweight aggregate concrete can be made by substituting pumice, low-density porous materials, synthetic lightweight aggregates, and even some organic aggregates for weightier crushed rock and gravel (Chandra, et al., 2003). Lightweight concretes may offer advantages in the reduction of weight, which can reduce transportation and emplacement costs, but must also offset any increased cost of production.

3.4 Case Studies: Bioengineered Breakwater Reefs

Cylindrical modular concrete unit emplacement patterns for submerged breakwaters are seen in Figure 3.1, below. These structures can also be emplaced to mimic the natural coastal zone environment. Over time, the structures become biologically dominated and can be classified as three-dimensional oyster reefs that serve as oyster broodstock sanctuaries within a given coastal zone ecosystem.

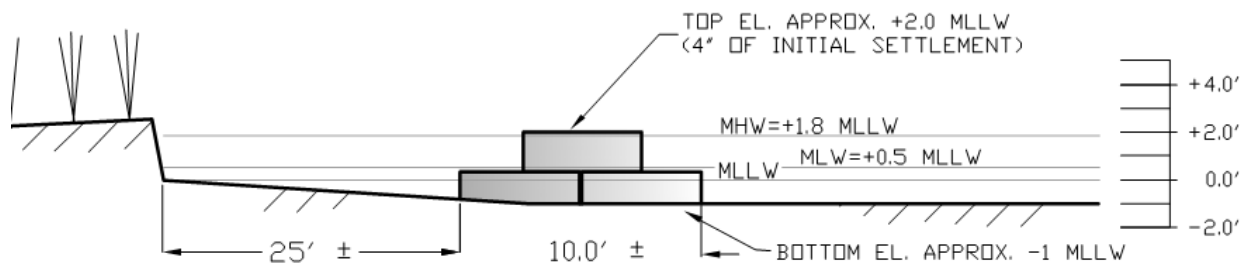
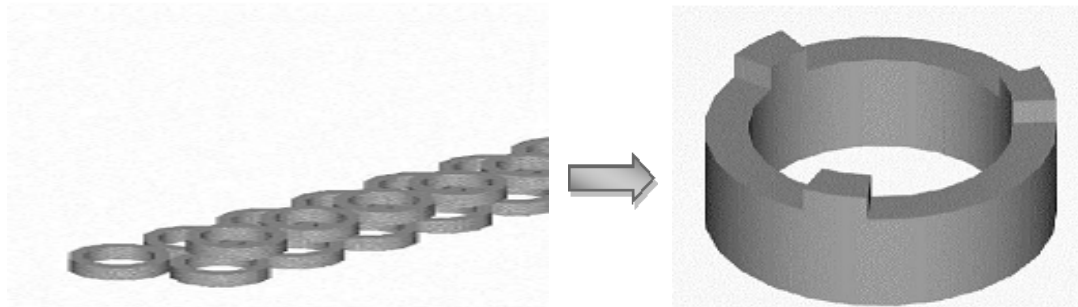


Figure 3.1: An example of a concrete modular unit breakwater structure. The large rings (2,000 lbs each) are designed to stay in place under severe wave action from a Category 3 hurricane (after Ortego, 2011).

3.4.1 Southwest Pass, Vermilion Parish (The Nature Conservancy)

Wayfarer Environmental Technologies (WET) manufactured OysterBreak™ rings for a project for The Nature Conservancy (TNC). The project site is located in Louisiana near Southwest Pass, Vermilion Bay, and it consists of approximately 350 concrete module units. This project employed multiple treatment scenarios comparing different concrete mixtures, emplacements, and design scenarios. Installation was completed in June 2010, and the site is monitored by the LSU School of Renewable and Natural Resources for shoreline effects, oyster growth, and biological utilization. Large shallow-draft barges fitted with cranes placed the singular concrete modular units within the intertidal coastal zone, conforming to breakwater system design conditions. Localized subsurface soil conditions were analyzed, along with tide, wind, and water wave data to optimize the design. This area has suffered from significant land loss, oyster reef

loss, and habitat loss over the past century. More recently, freshwater diversions that were opened in an attempt to minimize the effects of the 2010 oil spill and 2011 flooding have adversely impacted the environmental conditions for oyster growth.

The Vermilion Bay bioengineered oyster reef emplacements are in lower wave energy zones within the bay as compared to the Rockefeller project below and considered four treatment



Figure 3.2: Vermillion Bay Breakwater Demonstration Project (Risinger, 2011)

scenarios to facilitate biological and ecological activity with secondary breakwater effects. Low- and high-crested breakwaters, as well as gap spacing on segmented systems, are being tested. Total project costs are near \$1 million for approximately 3,000 linear feet of shoreline protection.

3.4.2 Rockefeller Wildlife Refuge, Cameron Parish (CWPPRA, LA-08)

The LA-08 demonstration project was funded by the Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA) and consisted of protecting approximately 1,000 linear feet of Gulf shoreline at Louisiana State Rockefeller Wildlife Refuge. The emplacement is 34-feet wide and constructed of approximately 1,700 concrete modular units (see Figure 3.3 below) in a grid

matrix configuration placed atop a lightweight aggregate geotextile sub-base. Total project costs are nearly \$2.3 million.



Figure 3.3: Rockefeller breakwater demonstration project (Ortego, 2012)

A key advantage in this application is that it overcomes extremely poor geotechnical conditions and high-energy wave action. The structure-bearing pressure on the soil is reduced to 284 psf, by installing the units on top of a marine geotextile mattress that distributes structure weight evenly on the underlying soils. Again, emplacement was conducted by a shallow-draft barge and crane unit. However, the contractor placed multiple rings (up to eight per load) onto the mattress, maximizing installation time. Two types of concrete rings were installed to evaluate and determine optimal biological growth conditions. This project was completed on February 14^t, 2012, and will be monitored by the National Oceanic and Atmospheric Administration (NOAA) and state agencies. This is the second commercial scale project completed within the Louisiana coastal zone.

The two case studies described above show different design scenarios consisting of high- and low-energy conditions and reveal opportunities to test alternate configurations in a pilot setting using alternate lightweight aggregates to reduce structure weight. The pilot experiment described below used smaller scale concrete modular units and evaluated alternate aggregate materials and emplacement configurations in low-energy zones to facilitate biological growth and leeward sediment accretion.

3.5 Theoretical Analysis of Varied Ring Geometries

Four different concrete ring dimensions were used in this experimental pilot study. The standard 3-inch ring-wall thickness was varied at 1, 1.5, and 2 inches. The 1-inch cross section ring's height was increased from 14 to 17 inches to evaluate tipping under wave action. The varied ring-wall thickness was used to evaluate physical properties under theoretical, lab, and field conditions. Autodesk Inventor Computer Animated Design was used to produce imagery and to describe physical material properties of the rings as depicted below in Figure 3.4. This program was also used to evaluate stress/strain relationships and displacement after point-force loadings (presented in subsequent sections).

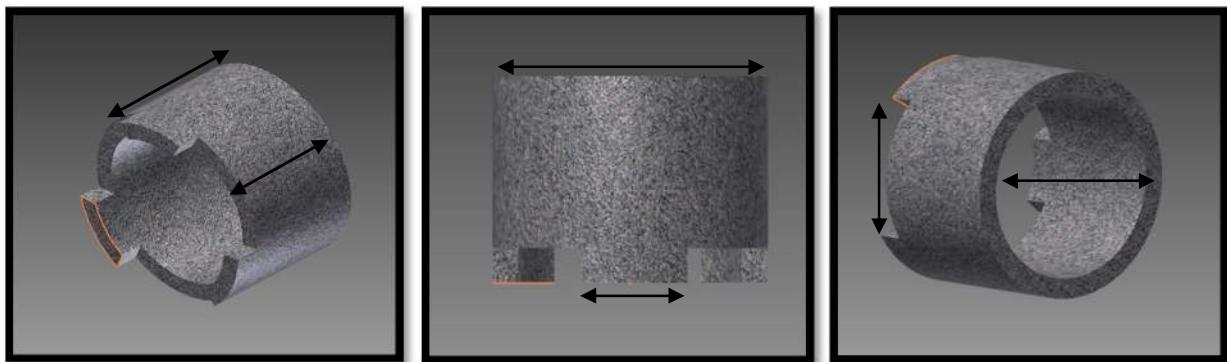


Figure 3.4 a, b, c: Autodesk 3-D imagery of ring geometry showing dimensions of 14 x 17 x 24 inches with 3 x 6-inch pegs.

These concrete rings were used in field test plots to slow the rate of erosion by dissipating wave energy and helping build up sediment along the coastline with biological oyster growth enhancing the process. The rings are made in different sizes, and each size ring has a corresponding amount of stress (experienced during manufacturing, transportation, or emplacement) it can withstand before deforming or failing. Table 3.1 below summarizes the geometrical design and physical properties of the varied ring dimensions. Using the engineering program Autodesk Inventor, the rings were modeled and analyzed under varied stress simulations as summarized below.

Table 3.1: Geometrical design and physical properties of varied ring dimensions

Physical Properties	1 Inch	1.5 Inch	2 Inch	3 Inch
Density (lb-mass/in ³)	0.036	0.036	0.036	0.036
Mass (lb-mass)	11	13	18	28
Surface Area (in ²)	1306	1069	1114	1210
Volume (in ³)	310	366	498	787

3.5.1 Force Load Simulation Model

Rings of varied dimensions made of ordinary Portland cement concrete with a standard yield strength of 2,903 psi were analyzed in Autodesk Inventor. Each simulation was also conducted at a modified yield strength of 500 psi. Each ring dimension was analyzed with respect to three different point-force loads: 1 lb, 10 lbs, and 100 lbs. The varying force loads can either represent different objects colliding with the rings resting in the water, or the forces can represent

collisions during transportation (after the rings are cured). For each simulation, the bottom surfaces of the rings' pegs were constrained to prevent movement, as if adhered to the seafloor, while the point forces were applied uniformly on each ring variant.

For every size ring, it is noted that the principal stresses, principal strains, and displacement increase by a factor of 10 for each increase in the applied force, from 1 lb to 10 lb to 100 lb.

Computer models were used to conduct stress analyses on the ring and bar structures, as illustrated in Figure 3.5 below. Twenty-four simulations were conducted, compiling data for the four different ring sizes, three varied loads of point forces applied, and two different yield strengths of ordinary Portland cement.

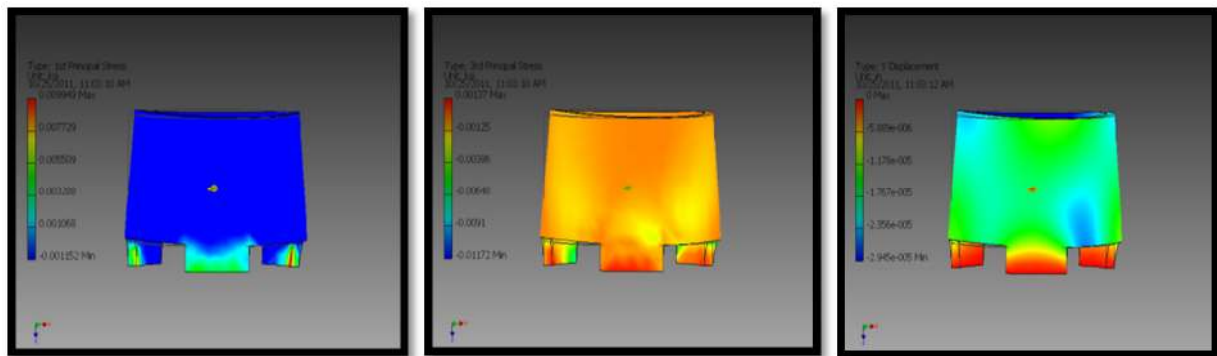


Figure 3.5: Autodesk image results under varied point force load deformation scenarios.

The 1-inch ring endured a maximum 1st Principal Stress of 19.85 psi on the bottom corners of the pegs. The deformation of the concrete was minimal, experiencing a maximum Displacement of 0.00006386 inches, indicating virtually no displacement on the structure. There is no failure in the material as shown by a universal safety factor of 15 around the ring. Duplicate results were obtained for a 1-inch ring with a 10-lb force and yield strength of 500 psi. These results are

summarized below in Table 3.2. Although a change in yield strength did not alter the results in the 1-inch cross section ring scenarios, a larger applied force produces a difference between any two rings.

Table 3.2: Autodesk image of ring displacement under varied point-force load deformation scenarios with 10-lb force and yield strength of 500 psi.

Ring Size	Max. Displacement (inch)	Max. 1st Principal Stress (kpsi)	Max. 1st Principal Strain (ul)
1 inch	6.38618E-06	0.00198359	9.34488E-07
1.5 inch	3.20872E-06	0.000994177	4.66044E-07
2 inch	2.07867E-06	0.000534034	2.48644E-07
3 inch	1.10542E-06	0.00031675	1.43288E-07

The following narrative illustrates a side-by-side comparison between two 1-inch rings applied with a force of 100 lbs and different yield strengths. Between the two 100-lb applied force scenarios for the 1-inch ring, the only factor to change with yield strength was the Safety Factor. Lowering the yield strength of the material from 2,903 psi to 500 psi proved to dramatically increase the chance of failure, lowering the minimum Safety Factor from 15 to 2.76. In these rings, the most likely point of failure is around the base of the pegs where the area is reduced. The only result that changed when comparing simulations of constant ring size and 100-lb applied force with the changing yield strength was the Safety Factor because the calculated stress has exceeded the yield limit of the material. Lowering the yield strength from 2,903 psi to 500 psi increases any ring's chance of failure for the 100-lb force, but the Safety Factor does not change with yield strength for the 1-lb and 10-lb forces for any ring size.

The 3-inch wall thickness ring proved most reliable for enduring impacts during application or transport. The stresses, strains, and deformation of the rings were proportional to the applied force, and these factors were not dependent upon the yield strength of the material. The smaller loads of 1 lb and 10 lbs were of no concern for inducing failure, and the 100-lb load only induced failure upon the modification of the material to a lower yield strength. A graphical summary of 1-lb forces are presented below in Figure 3.6 a, b.

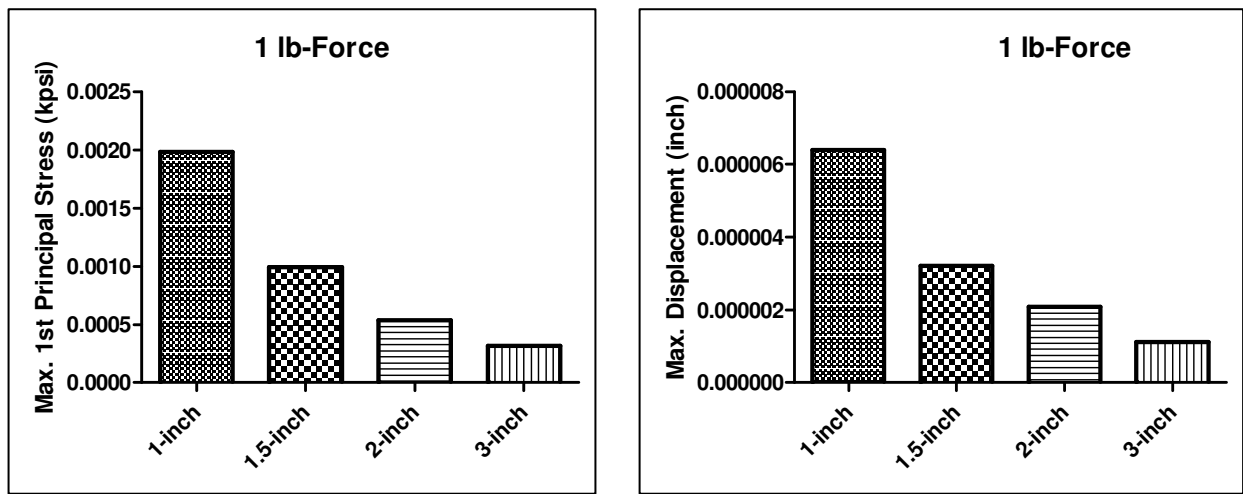


Figure 3.6: 1 lb Force results for varied ring wall thickness (a) maximum 1st principal stress (kpsi), and (b) maximum displacement (inch).

3.6 Lab Analysis of Concrete Modular Units

Concrete modular units were manufactured in a laboratory setting to provide controlled conditions capable of producing uniform products for field installation. Sheet metal was manipulated and used to form inner and outer rings to achieve specified structure cross-sectional wall thicknesses of 1, 2, and 3 inches. PVC pipes were measured and cut to hold the metal forms in place. Wood “peg legs” were measured, sawed, beveled, and nailed in order to be placed at

equal spacing in the ring molds to create a locking mechanism for stacked concrete units. These pegs also serve in emplacement on the sea floor, securing the structure in place, and minimizing settlement. Wooden “toppers” were measured, sawed, beveled, and cut, and placed on the top of the formed molds to enhance pour efficiencies. The finished form molds were then placed on plastic sheets and covered to ensure constant environmental conditions on all pours. After 24 hours of curing time, the forms were removed and the rings were allowed an additional 24-hour curing period before being transported or stored. The process is shown in the following figure.



Figure 3.7 a, b: (a) Form set-up and (b) form removal (Risinger, 2011).

The concrete was mixed in a round barrel mixer. The mixture used was of a lower water to cement ratio ($< 1:4$ or 0.25) and included the addition of agricultural byproducts to facilitate oyster settlement and recruitment. After mixing, the concrete was transferred to the forms. Three ring fractures were recorded in the lab setting, while no ring fractures occurred during transport and emplacement. Ring fractures occurred on the pegs, and one lateral seam fracture line appeared after a unit was dropped during stacking.

3.6.1 Batch Mixtures and Alternate Aggregates

Ordinary Portland cement was used in laboratory test batch mixtures, along with varied aggregates, to determine the optimal strength-to-weight ratios for emplacement scenarios as biologically dominated, engineered artificial oyster reef technologies serving as breakwater systems. Aggregate variations included available graded limestone rock (hereafter dolomite), vitrified expanded clay, lava rock, and oyster shells matrices. Mixtures were varied (as summarized in Table 3.3 below) with a standard low water-cement ratio, sand, and organic agricultural byproduct ingredients. Six sets of test cylinders were prepared for each varied aggregate mixture, resulting in 30 test cylinders that were allowed to wet cure and subsequently weighed and analyzed for 28-day material strength testing (compression and flexural).

Table 3.3: Batch mixture designs for experimental ring pilot study

MATERIAL	Weight	Dolomite	Dolomite /Clay	Lava Rock/Clay	Oyster Shell	Clay
Aggregate 1	(g)	29,483.50	11,339.81	6,350.29	22,679.62	13607.77
Aggregate 2	(g)	0.00	6803.89	6803.89	0.00	0.00
Cement	(g)	2,122.20	2,122.20	2,122.20	2,122.20	2,122.20
Sand	(g)	1,672.40	1,672.40	1,672.40	1,672.40	1,672.40
Water	(g)	1,444.00	1,444.00	1,444.00	1,444.00	1,444.00
Organic	(g)	20.00	20.00	20.00	20.00	20.00
Avg. Cylinder	(g)	2,736.33	1,743.02	1,768.48	1,629.35	1,392.17

Aggregate variations resulted in different material densities that can be related to bearing pressure (weight), which is an important design element when considering site-specific geotechnical conditions. Effective density variations are summarized below in Table 3.4.

Table 3.4: Batch mixture design densities

	Unit	Dolomite	Dolomite /Clay	Lava Rock/Clay	Oyster Shell	Clay
Density	(kg/m ³)	1,661	1,058	1,074	1,286	1,099
Cylinder	(kg)	2.736	1.743	1.768	1.629	1.392

*Density of ocean water at the sea surface is about 1,027 kg/m³.

Each test cylinder was weighed on an electronic scale calibrated in the lab. The tare weight was subtracted from the cylinder weight to determine the actual batch weight of each test mixture as depicted below in Figure 3.8.

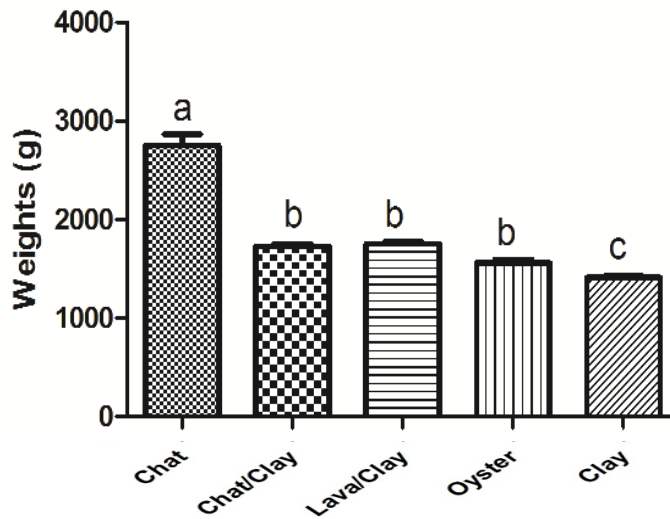


Figure 3.8: Five groups of concrete aggregate mixtures analyzed by weight with notable significant differences ($P < .0001$) using a one-way analysis of variance (ANOVA); and Tukey's Multiple Comparison Test revealed significant differences ($P < .05$) as denoted above by lower-case letters.

The dolomite mixture exhibited the highest statistical weight of all mixtures, followed by statistically similar weights for the chat, clay, lava, and oyster aggregate mixtures. The clay mixture was statistically lighter than all aggregate mixtures ($P < 0.0001$). It is produced by

expanding and vitrifying select shales, clays, and slates in a rotary kiln. The process produces a consistent high-quality ceramic aggregate that is structurally strong, physically stable, durable, environmentally inert, and light in weight. It is a non-toxic, absorptive aggregate that is dimensionally stable and will not degrade over time.

3.6.2 Concrete Material Strength Testing—Compression

Concrete test cylinders and biologically dominated concrete specimens were analyzed for weight and flexural and compressive strength characteristics (stress and strain relationships). Concrete flexural strength and compression testing was completed at the Louisiana Transportation and Research Center (LTRC) under direction of Dr. Tyson Rupnow, Ph.D., P.E., using an FX Series Forney Premium Compression Machine and a Standalone Forney Beam Tester using appropriate ASTM standards administered by LTRC staff.

Thirty wet-cured test cylinders were prepared using varied aggregate mixtures and analyzed for 7- and 28-day compressive strength using FX Series Forney Premium Compression Machine according to ASTM C39—Compressive strength. Figure 3.9 below shows the equipment and set-up for testing. Each specimen was weighed, measured, and programmed into the machine for testing.



Figure 3.9 a, b: (a) FX Series Forney Premium Compression Machine, and (b) batch test cylinders.

Figure 3.10, below, summarizes graphical results of the 28-day Compressive Load Strength testing procedures related to load and stress. The oyster shell exhibited the only statistically significant strength results, likely due to the reduced bonding surface area provided by the shells. It is also presumed an error occurred in one of the chat/rock test cylinders, providing misleading statistical results. With an outlier observed and omitted, the dolomite/clay aggregate exhibited the highest statistically significant strength results when compared to the other aggregate mixtures. Three aggregate mixtures (dolomite/clay, lava/clay, and clay aggregates) experienced statistically similar test results for 28-day strength testing.

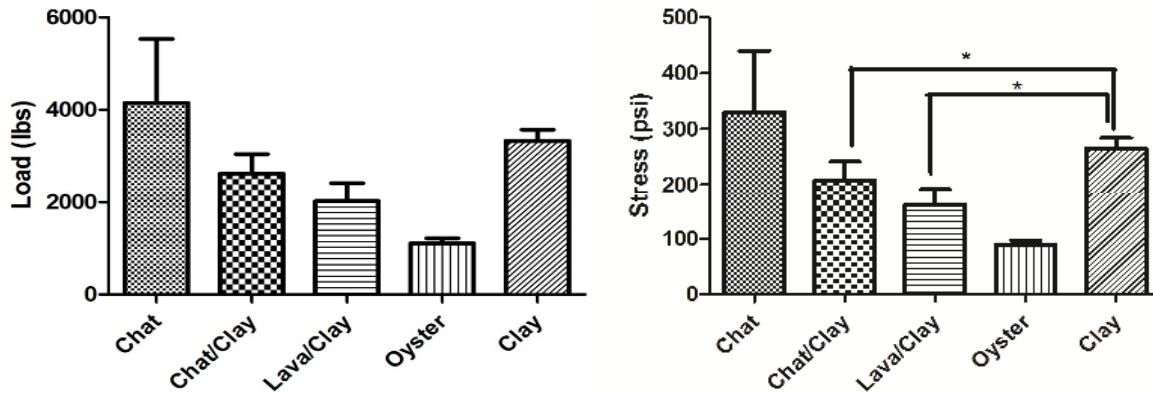


Figure 3.10: (a) Compression load results in lbs of five groups of aggregates, and (b) stress comparisons in psi showing no significant differences denoted by asterisks (ANOVA, $P < 0.001$).

The lightweight aggregate showed no statistically significant difference in Compressive peak load strength (3,328 lbs with $P < .001$) when compared to other alternate aggregate batch mixture designs. Lightweight aggregate concrete mixtures (i.e., vitrified expanded clay) showed optimal Compressive peak load strength and weight ratios when compared to traditional aggregates weighing less than 50% by volume with comparable strengths to traditional limestone/dolomite aggregate mixtures (chat). The resulting strength and weight of this type of aggregate could prove to be an optimal design scenario for soft soils in the Gulf of Mexico; however, additional monitoring of biological activity is necessary to prove this material as a viable source of aggregate for artificial reef substrate. Cost variations in lightweight aggregates are also of consideration, as discussed later.

3.6.3 Biological Material Strength Testing—Flexural

Concrete bars consisting of rock aggregate and standardized Portland cement mixtures were analyzed for flexural material strength using a Standalone Forney Beam Tester in accordance

with ASTM C78–Flexural Strength. The bars tested had varied oyster growth over time from previous research pilot studies at Rockefeller Wildlife Refuge. Figure 3.11 shows machine and set-up testing procedures. A standardized cross section was used for all specimens.



Figure 3.11 a, b: (a) Standalone Forney Beam Tester and (b) log specimen.

Figure 3.12 summarizes peak flexural load relationships among the three different oyster growth durations from pilot reefs within the study area. Significant increases in overall flexural strength of the beam were exhibited over time, in part due to oyster growth on the concrete scaffolding structure. Additional factors that may increase material strength over time in a marine environment include varied concrete mixtures among reefs and normal hardening over time.

Biologically dominated concrete structures showed a significant increase in strength over time from an initial 28-day peak curing load of 100 lbs to peak loads of 479 lbs in six months and 1,344 lbs in two years. A uniform cross-section was used in all analyses. This significant

increase in strength is likely due, in part to the biological oyster growth over time that encapsulates the concrete.

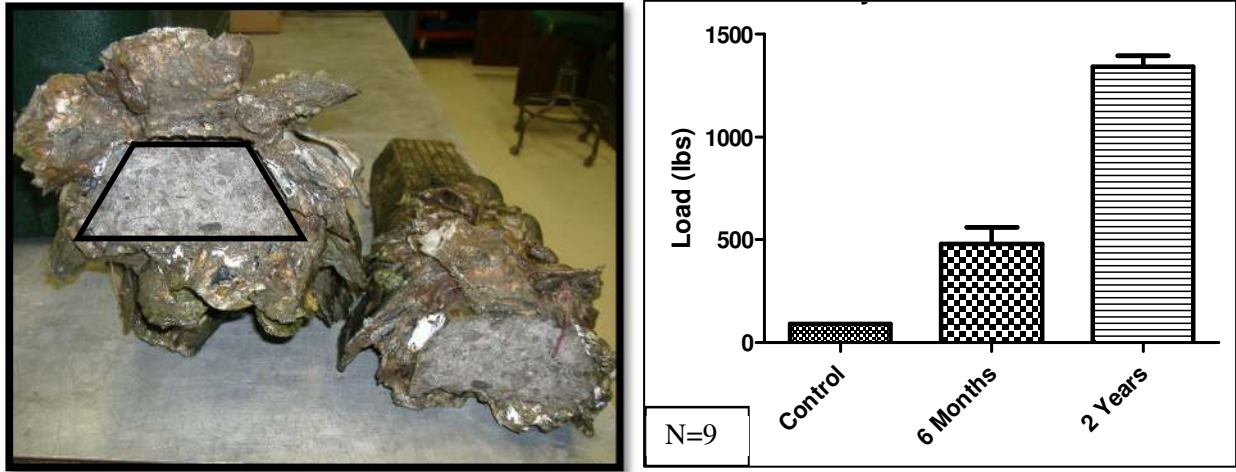


Figure 3.12 a, b: (a) Concrete with oyster growth (b) flexural strength variations over time.

3.7 Field Conditions for Pilot Scale Emplacements

An initial ring emplacement took place at Rockefeller Wildlife Refuge on March 17th 2011, to begin the field pilot study, which was used as testable comparisons with previous test plots.



Figure 3.13 a, b, c: Rockefeller Wildlife Refuge pilot experiment emplacements (2011)

This configuration, as seen above, was placed along a tidally influenced navigation canal shoreline to imitate a segmented intertidal breakwater system. A “skipjack” boat was used to

transport the rings to the project site. Human labor was used to emplace the rings into three different formations: a heavy emplacement of 14 rings, a medium emplacement of four rings, and a lighter emplacement of two solo rings. These configurations are depicted later in Figure 4.5. Several subsequent emplacements took place with varied dimensions, aggregates, and configurations that are currently being monitored for future research applications.

Bioengineered concrete facilitates oyster settlement through the addition of organic agricultural compounds (i.e., cotton seed), which decay over time and emit ammonia that attracts spatfall. This oyster growth over time increases the structural integrity of the concrete rings as they become biologically dominated. Experiments were conducted with varied aggregate mixtures (as described earlier) used to form rings of different wall thicknesses for strength testing. Concrete “log” specimens with oyster growth were collected over time and tested for flexural strength relationships facilitated by biological growth. The reefs were also monitored for sediment accretion and biological growth, which are summarized in separate chapters.

Rings of all sizes were successfully transported to the field and installed at the Rockefeller Pilot Bioengineered Oyster Reef site. More than 30 rings were used in these field pilot studies. Standard 3-inch-thickness rings were used on subsequent reef installations, with one reef using six lightweight aggregate rings emplaced on a geotextile marine mattress. An existing biologically dominated reef and associated sediment are shown below in Figure 3.14. This is an existing pilot reef site emplaced to facilitate wave attenuation, to minimize erosion, and to promote sediment accretion behind the breakwater structure. A salient sediment feature can be observed, along with the cylindrical reef figures biologically dominated by oyster growth.



Figure 3.14 a, b: Rockefeller Wildlife Refuge pilot breakwater structures (2012)

After emplacement at the experimental pilot site, these artificial concrete reef structures were monitored to evaluate biological activity by oyster growth, any increasing shoreline protection, and ecological benefits. The biological growth may increase the overall structural integrity of the reef to provide a long-term, sustainable solution to mitigate coastal land loss.

3.8 Scalability, Costs, and Limitations

The cost of breakwaters increases dramatically with water depth and wave climate severity, with poor foundation conditions significantly increasing costs (CEM, 2006). These three environmental factors heavily influence the design and positioning of the breakwaters (NCDRCM, 2006). Planting vegetation or installing living shoreline breakwater systems, or a combination of both might provide cost-effective shoreline protection while maintaining natural coastal processes (MASGC, 2007).

Rubble-mound offshore breakwaters costs relate to riprap material (20-35 \$/yd³) and installation labor and materials (150-200 \$/ft). Additional construction costs may be incurred for

mobilization, demobilization, and unforeseen conditions. Based on a 1,000 linear feet of breakwater with a 50 ft² cross-sectional area, estimated costs associated with this type of system would be \$210,500. Traditional concrete modular units have been installed for \$500 per unit (5-ft diameter), or \$100/ft. This would equate to as little as \$100,000 for 1,000 feet of shoreline protection. Current estimated costs of a 1,000-foot OysterBreak system (at \$325/ft as obtained from the manufacturer) would total \$325,000. Generally, concrete armor units are made of conventional unreinforced concrete, except for some of the multi-hole cubes where fiber or other reinforcement is used (e.g., various types of high-strength concrete and reinforcement have been considered), but these solutions are generally less cost-effective (CEM, 2006).

Aggregate materials also vary in initial cost and freight. Limestone aggregate rock from Bear Industries in Port Allen sells for \$35/ton, with freight costs of nearly \$25/ton for 100-mile transport. Lightweight aggregate material from Old Castle in New Roads sells for \$35/yd³, with two yards equaling one ton of mass. Lightweight aggregates can reduce overall project costs by increasing product volume and reducing mass, thereby reducing freight weight. However, this type of aggregate material may be limited biologically, and additional research is needed to further understand its interaction within a marine environment.

3.9 Discussion and Conclusion

Cylindrical concrete modular units were employed to evaluate the use of biologically dominated breakwater reef technologies as engineered structures comprised of alternate lightweight aggregates. In some cases these units comprised less than 10% by weight total mass of traditional rock breakwater structures. Aggregates were also varied in concrete mixtures to determine optimal strength and weight ratios. Lightweight aggregates (i.e., vitrified expanded

clay) showed optimal strength and weight when compared to traditional aggregates, with no statistically significant difference in strength (3,328 lbs with $P < .001$) and weighing less than 50% by volume. Alternative lightweight aggregates such as vitrified expanded clay materials need to be tested in a marine setting to evaluate their strength and biological reactivity in the intertidal zone. This should be a focus of future research efforts related to optimizing the design of biologically dominated detached breakwater systems using lightweight aggregate additives.

Existing biologically dominated concrete structures showed a significant increase in flexural strength over time from an initial 28-day peak curing load of 100 lbs to peak loads of 479 lbs in six months and 1,344 lbs in two years. These results indicate that a relatively weak initial structure might become biologically dominated by oyster growth and become stronger over time through the cementing calcification process of oyster shells. Biological monitoring and sediment bathymetry surveys on these pilot scale experiments are on-going to further quantify characteristics and effects of concrete modular artificial reef technologies to qualify them as viable and sustainable biologically dominated breakwater systems for coastal protection and restoration in the Gulf of Mexico.

3.10 Recommendations

Based on a combination of results from material testing of varied aggregates, the vitrified/expanded clay exhibited optimal strength and weight for use in concrete ring modular units and emplacements. These rings should be experimentally installed and their performance monitored in a marine environment, with a focus on biological reactivity and wave hydrodynamic interaction. Additional lightweight aggregates (EcoSlag Pozzoloans) should also be explored and monitored for similar field test parameters. Future research components could

include the additional of alternate cement additives such as slag, class C fly-ash, and industrial byproducts like gypsum. These alternative aggregate and concrete substitutes may provide a solution that will lessen economic costs related to manufacturing, transport, and installation—if the costs outweigh the benefits of the biological monitoring yet to be conducted. In some cases, depending on water depth, subsurface soil conditions, and wave energy, traditional rubble-mound breakwaters may prove to be more cost-effective when compared to biologically dominated artificial reef technologies that are limited to certain environmental conditions within the intertidal zone.

Flexural strength testing of concrete material dominated by biological growth over time showed increased flexural strength results over time, which can be partly attributed to the oyster growth. Additional long-term studies in controlled environments should be conducted using alternative lightweight aggregates and cement additives to determine the relationships among material strength, aggregates, cements, and biological growth. These types of studies will allow a better understanding that can optimize the design of biologically dominated concrete module units for breakwater emplacements.

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Pending Patent:

Artificial Material Conducive to Attract and Grow Oysters, Mollusks or Other Productive and/or Stabilizing Organisms. Reapplication pending 2011, US Patent Application No. 11/428,060; 20100126425.

Licenses:

Biologically Dominated Artificial Reef. Released by LSU AgCenter 2005. Licensed to Wayfarer Environmental Technologies, 2006; license updated 2010.

CHAPTER 4: SEDIMENT ACCRETION AND BATHYMETRY PROFILE MONITORING OF EXPERIMENTAL BIOLOGICALLY DOMINATED INTERTIDAL BREAKWATER REEFS

Louisiana is experiencing significant coastal erosion and lacks sustainable infrastructure for shoreline protection. Intertidal coastal breakwaters can mitigate land loss and facilitate sediment accretion by reducing wave energy. Sediment accretion can increase over time as the structures become biologically dominated by oyster growth. An experimental study was conducted in the Rockefeller Wildlife Refuge to monitor sediment accretion rates behind intertidal breakwater structures serving as artificial oyster reefs. Three structures were surveyed with laser equipment and related to a GPS-established benchmark. Each experimental breakwater emplacement exhibited sediment accretion, with the biologically dominated structure showing significant sediment accretion when compared to the other more recently installed structures. Pilot scale breakwater emplacements dominated by biological growth accumulated nearly 4 m³ of sediment over four years. Heavy and light ring density emplacements installed for less than one year accreted 1.6 and 0.37 m³ of sediment, respectively. Biologically dominated intertidal breakwater systems may prove to be a viable contribution to coastal shoreline protection and restoration efforts in the Gulf of Mexico.

4.1 Introduction

Natural and anthropogenic factors have caused the coast of Louisiana to lose land at high rates, and compared to historical levels over the past century, 50% of the nation's wetlands have disappeared (Dahl, 2006). In southwest Louisiana, the Rockefeller Wildlife Refuge is experiencing long-term shoreline retreat at a rate of 30 to 40 feet per year (Byrnes et al., 1995). The coast of Louisiana has been affected by a variety of factors such as climate change, land

subsidence, sea level rise, hurricanes, and lack of sediment supply. To promote shoreline stabilization, coarse material may be used to reduce wave and other erosive energies along eroding marsh and estuarine shorelines, and oyster reefs have been hypothesized to have similar beneficial effects (Piazza et al., 2005). Oyster reefs also promote the stabilization of shorelines by binding together and colonizing to form reefs in three-dimensional spaces via the crystallizing cement of calcium carbonate these bivalves produce (Harper, 1997).

In aquatic habitats, mollusk shells exist as abundant, persistent, ubiquitous physical structures; and oysters exist as fecund, colonial, hermaphroditic, and sessile organisms capable of armoring entire shorelines. General roles of oyster shell production in coastal restoration and habitat management are identified through the application of an ecosystem engineering perspective (Gutiérrez et. al., 2003). These reefs can be bioengineered by artificially creating a scaffold for oyster growth, resulting in a biologically dominated structure and living shoreline. Living shorelines serve multiple roles by controlling erosion, maintaining natural coastal processes, and sustaining biodiversity through land-use management, soft armoring, or combinations of soft and semi-hard armoring techniques. They provide a viable alternative to common hardened structures such as bulkheads, stone revetments, and seawalls (Swann, 2008).

In this experiment, bathymetry surveys were conducted on pilot scale artificial coastal breakwater reefs at Rockefeller Wildlife Refuge in order to quantify sediment accretion by these biologically dominated structures. Reference surveys were conducted to determine field baseline bathymetric topographic conditions. Permanent benchmarks were established and correlated to mean sea level using a GPS OPUS interaction. This data was used to analyze sediment accretion behind the breakwater reefs.

4.2 Background

Oysters form reefs that affect wave transformation. Wave transformation processes that occur across broad, flat reefs include: shoaling, refraction, reflection, and energy dissipation by both bottom friction and wave breaking (USACE-CEM Part VI, 2006). Wave energy is also transferred to both higher and lower frequencies in the wave spectrum, as the spectral shape flattens across the two-dimensional reef (Hardy and Young 1991). A methodology to estimate random wave energy transformation across reefs is based on the breaking wave model of Dally et al. (1985) and extended to random waves following Kraus and Larson (1991). Oyster reefs, which dissipate wave energy, can be used as intertidal coastal breakwaters to facilitate sediment deposition and to protect shorelines from erosion.

4.2.1 Detached Intertidal Breakwaters

Offshore breakwaters provide a physical barrier that dissipates wave energy through wave diffraction, dissipation, and reflection (Dehon, 2010; Benassai, 2006; Campbell, 2004 and CCEZM 1990). Breakwaters are typically constructed from rock, cement armor stones, sunken barges or ships, or any heavy objects that break up wave action (CCEZM, 1990). Breakwaters are typically segmented in the intertidal zone and detached from the shoreline; thus, they provide optimal protection while allowing water, sediment, and aquatic organisms to pass through. These barriers also provide a sheltered area that serves as a reservoir for sediments carried by the diffracted waves (Benassai, 2006). These provide a similar effect as a sediment fence, which is used to promote sedimentation (Scarton et al., 2000). As the sediment builds up over time, the breakwaters create salients and sometimes tombolos as the shore connects to the breakwater (Chen, 2008).

The use of offshore breakwaters as a means of beach protection and passive nourishment has increased more quickly than the use of groin-type structures in the last decade. This shows a strong trend toward the use of breakwaters as a means of beach protection and stabilization (Benassai, 2006). However, traditional breakwaters do not maximize the environmental and ecological benefits that can be incorporated by a biologically dominated reef. Further, traditional rock breakwater structures may require significantly more materials for emplacement and require long-term maintenance as the material settles in the soft soils. Providing a breakwater reef substrate of lesser weight that is conducive to biological growth may increase long-term effectiveness of this type of technology by limiting future repair and maintenance costs.

4.2.2 Segmented Breakwaters and Sediment Accretion

Within a breakwater system, sediment transfer occurs via wave energy hydrodynamics and littoral sediment transport. Reducing wave energy to allow sediment accretion is the main design goal of detached breakwaters. Sea level rise and hurricanes can also stimulate sediment transport, which is impacted on a much greater system scale by these major events (Chasten et al., 1993).

Detached breakwaters are used as an applicable method for sustainable shoreline protection in the United States. These breakwaters may be designed for multiple uses by employing a variety of emplacement configurations. For example, wetlands and estuarine shorelines are using a mixture of low-crested breakwaters and planted marsh grasses are being used to protect wetland and estuarine shorelines (Chasten et al., 1993). Offshore breakwaters can be built as either a single structure or in a series. A single structure only protects a localized area; on the other hand, a series of structures guards an extended length of shoreline. A series is also known as a

segmented system; it contains two or more structures divided by gaps with specific widths (Birben and Özölçer, 2007).

Most nearshore breakwaters built in the United States for shore protection have been rubble-mound type structures that have proven design elements but may lack long-term sustainability and may require maintenance to account for structure settlement in soft soils. Alternative methods such as concrete modular units are relatively new but may prove a more long-term viable solution than rubble-mound breakwaters. Several patented, nontraditional precast concrete units have been used in the United States, producing similar functional performance. Their success has been: (a) a function of structural stability of the units during storm conditions, (b) their durability over an economic life and (c) by maintaining the design crest elevation for wave energy reduction (USACE-CEM Part VI, 2006). The need to reduce impact on the environment is increasing the necessity for further research and comprehensive field testing programs for nontraditional designs (USACE-CEM Part VI, 2006).

Some concrete modular units can become biologically dominated when placed in the intertidal zone and serve as artificial reefs. The functional design of artificial reef systems for shore protection is a relatively new area of coastal engineering; therefore, no general design rules exist (USACE-CEM Part VI, 2006). Prototype experience for the functional design of near shore breakwaters in the United States is generally limited to sediment-starved shores in the Gulf of Mexico (Pope et al., 1986).

The primary function of nearshore breakwaters is to reduce offshore sand transport during storms and to reduce onshore sediment movement during normal, swell wave conditions that naturally rebuild the beach (USACE-CEM Part VI, 2006). A salient sediment response is the preferred

shoreline response to a detached breakwater system designed for the U.S. Army Corps of Engineers, as stated by Chasten et al. (1993). A salient response (Figure 4.1, below) allows long-shore sediment transport to continue through the project area to down-drift beaches. Salients are likely to predominate when the breakwaters are sufficiently far from shore, whereas tombolos form in conditions where the breakwater is long or located close to the shore or both. However, a breakwater that is long and is a great distance from the shore will favor the formation of salients. When systems are partly submerged and contain large gaps, they become permeable and allow sufficient wave energy that minimizes the chance of tombolo formation.

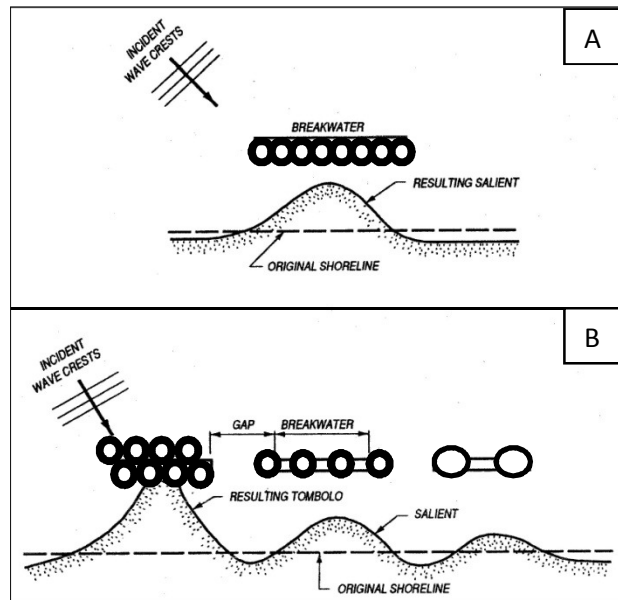


Figure 4.1 a, b: (a) Long offshore breakwater configuration favoring salient response and (b) nearshore breakwater configurations of heavy, medium, and light placements with associated shoreline response (after USACE-CEM Part VI, 2006)

Figure 4.1 above illustrates ring breakwater configurations and associated shoreline sediment response within a coastal system. Long offshore ring configurations favor salient formations, as do shorter, segmented breakwaters closer to shore. Heavier ring placements nearer the

shoreline will favor a tombolo sediment response. Both sediment responses can be utilized for vegetative plantings to further protect the shoreline from wave energy.

For salient or tombolo formation, the key breakwater variables affecting wave hydrodynamics are listed as follows:

Y, Distance of breakwater from nourished shoreline

Ls, Length of breakwater structure

Lg, Gap distance between adjacent breakwater segments

ds, Depth (average) at breakwater structure below mean water level

Three dimensionless ratios, Y/ds , Ls/Lg and Ls/Y have emerged to separate salient and tombolo response. When the breakwater is long and/or located close to shore, conditions favor tombolo formation.

Many references suggest $Ls/Y > 1-2$ for tombolo formation; Dally and Pope (1986) recommend:

$$Ls/Y > 1.5-2 \text{ for single breakwater} \quad (\text{Equation 4.1})$$

$$Ls/Y = 1.5 \text{ for segmented breakwater } (Lg < Ls) \quad (\text{Equation 4.2})$$

Ahrens and Cox (1990) also defined a beach response index, I_s :

$$I_s = \exp(1.72 - 0.41 Ls/Y)$$

Where a well-developed salient type of beach response is preferred, Pope and Dean (1986) give an I_s value of 3. The ratio Ls/Lg is also important for salient or tombolo formation. Large gaps will let more wave energy reach the shore to promote salient formation. And this value will coincide with smaller Ls/Lg ratios. The Japanese Ministry of Construction presents a step-by-

step interactive procedure for nearshore breakwater design (Japanese Ministry of Construction, 1986).

4.2.3 Regional Sediment Management in the Coastal Zone

The concept of Regional Sediment Management (RSM), derived from the Army Corps of Engineers (USACE) in the early 1990s, is related to conservation and management of sediments in the littoral zone and attempts to “design with nature,” utilizing an understanding of sediment movement in a region and the interrelationships of projects and management actions for ecosystem restoration and protection (Martin, 2002). Originally related to beneficial uses of dredged material, RSM now covers linkages to riverine system dynamics and freshwater diversions. Large-scale freshwater diversions (e.g., Caernarvon Outfall) have been operating in Louisiana for many years for flood control, but these same diversions are now being evaluated for their ability to restore marshes and wetlands, as well as oyster public seed grounds. Large-scale and small-scale freshwater diversions and combinations of both can be used for coastal protection and restoration (Martin, 2002) because the waters they redirect are rich in sediment.

The channelization of the Mississippi River has altered native ecosystems and caused some land loss in coastal Louisiana by cutting off the sediment it historically supplied. Oysters are an organism that likely will be closely monitored in river diversion scenarios. The use of bioengineered oyster reefs in these diversion areas will be a focus of additional study to evaluate the suitability of these systems as breakwater structures.

4.2.4 Commercial Scale Breakwater Reef Emplacement

Bioengineered artificial oyster reefs combine concrete with agricultural byproducts in formed shapes for emplacement in the intertidal coastal zone where oysters can attach and grow. These reefs become biologically dominated, which increases their ability to perform natural functions like habitat creation, shoreline protection, and many more ecological benefits. Emplacing these large structures requires a significant amount of planning and design. Many times the structures are fabricated in distant locations, requiring transportation to site-specific installations along the coastal zone. On large-scale commercial projects, hundreds of two-ton concrete rings are hauled hundreds of miles and loaded onto shallow-draft barges fitted with cranes for expedited installation and emplacement. Smaller pilot projects can emplace research rings, typically weighing less than 50 lbs, with only the use of human labor and boats. Any placement of bioengineered artificial oyster reefs requires a significant amount of planning and design to ensure optimal performance of the biologically dominated structures. Improper planning and design can leave structures stuck in the mud, uninhabitable by oysters, and may actually cause erosion.

Cranes and barges are typically used to install larger commercial-grade rings in the coastal zone. A one-ring placement can take up to several minutes, depending on site conditions. New methods have been developed by contractors to expedite placement and to drastically reduce installation costs. In some cases (see Figure 4.2, below) multiple rings can be emplaced simultaneously with a truss method. This allows for multiple rings to be emplaced with proper spacing and alignment. The rings are pre-cast with pinholes, which can be used to secure and lift the structure(s) into the water. A “spotter” in the water provides pinpoint location and releases the pins once final placement location is reached.

Local geotechnical conditions are also an important design consideration. In areas with low-bearing pressure soils, engineered geotextile mattresses should be used beneath the ring emplacements to prevent sinking and scouring potential by spreading out the load distribution.



Figure 4.2 a, b: CWPRA demonstration project, Rockefeller Wildlife Refuge (2012)

These underlying mattresses can also increase the bioproductivity of an artificial reef by increasing the surface area of suitable substrates available for bivalve settlement. Once the entire system is installed, a sustainable reef is ready to become biologically dominated and blend into the environmental settings within several years.

Shallow-draft barges are ideal for installing artificial reefs within the coastal zone. By monitoring the tides, emplacement can be accomplished with relative ease by an experienced contractor. Other methods for shallow-water installation require the use of an airboat and crane. This technique only allows for a smaller payload, but navigational freedom is attained by the operator.

Smaller rings can be used by homeowners or for research purposes. Depending on the aggregate mixtures and size of rings installed, the weights are generally manageable (under 50 lbs). These

rings can be installed as revetments or “sills” along the intertidal shoreline at camps or places that exhibit erosion. The rings can also be loaded into boats and transported to other sites suitable for a biologically dominated artificial oyster reef (i.e., canal banks, marsh fringes, piers, or cheniers). In this case, a general design methodology should be followed, depending on the desired use as a breakwater or revetment, and both should be installed in the intertidal zone to maximize ecological benefits of oyster populations. The rings should not be installed in known navigational waterways without proper U.S. Coast Guard signage, as serious injury could result from impact.

4.3 Materials and Methods

4.3.1 Pilot Scale Experiments

Cylindrical concrete modular units (rings) were manufactured in a laboratory setting and used for experimental pilot breakwater reefs. An initial ring emplacement was conducted at Rockefeller Wildlife Refuge on March 17, 2011, to begin the field pilot study, which was used as a testable comparison with previous test plots installed in 2007 and 2009. Additional pilot reefs were installed in April, June, and December 2011 to imitate a segmented breakwater emplacement. Figure 4.3 below shows transport and installation, as well as a final heavy emplacement of a three-dimensional high-relief breakwater reef.

These configurations, as seen below, were placed in sets of three along the shoreline to imitate a segmented intertidal breakwater system. A “skipjack” boat was used to transport the rings to the project site, and human labor was used to emplace the rings into the different formations. These test plots are being monitored for oyster biometrics, material strength, and sediment accretion.

Three particular reefs are of interest for sediment accretion, monitored by bathymetry profiling. The existing bioengineered oyster reef configuration was placed at Rockefeller Wildlife Refuge three years ago. Sediment accretions behind these three reefs were compared. Baseline control transects were obtained from undisturbed shoreline and used for comparison to the other reefs.



Figure 4.3 a, b: Transportation and emplacement of pilot reef breakwater at Rockefeller Wildlife Refuge (Jon Risinger. March, 2011)

Future research should include ongoing monitoring of sediment accretion rates behind new reefs to determine long-term bathymetry profiles, sediment accretion rates, and biological growth.

4.3.2 GPS Benchmark

An original temporary benchmark was established on a “No Wake Zone” wood pylon near the project site. This benchmark was calibrated to mean sea level (MSL) with a TopCon GRS-1 global positioning system (GPS) dual-frequency, 72-channel GPS + GLONASS real-time kinematic (RTK) rover receiver with TopCon PG-A1-6 external antenna on TopCon 2 meter fixed-height range pole. A secondary temporary benchmark was established on the shoreline ridge with a 4' x 1/2" steel rebar rod driven into the ground with two feet of exposure.

A static “occupation” was taken for two hours. This data was submitted to NGS OPUS (National Geodetic Survey Online Positioning User Service) after two weeks to obtain horizontal and vertical solutions using precise orbits. Solutions calculated relative to North America datum (NAD) 83 (CORS96, MARP00, PACP00) epoch 2002.00. In the passing of two requisite weeks after the static data collection and preliminary OPUS solution, the dataset was resubmitted to OPUS to obtain a new OPUS solution based on the "precise" orbits. The original OPUS-estimated orthometric height was 1.288 meters (4.2257 feet.). Using the precise orbits, the orthometric height of the temporary benchmark calculated was 1.297 meters (4.2552 feet.) AMSL. Survey, GPS, and laser leveling equipment are pictured below in Figure 4.4.

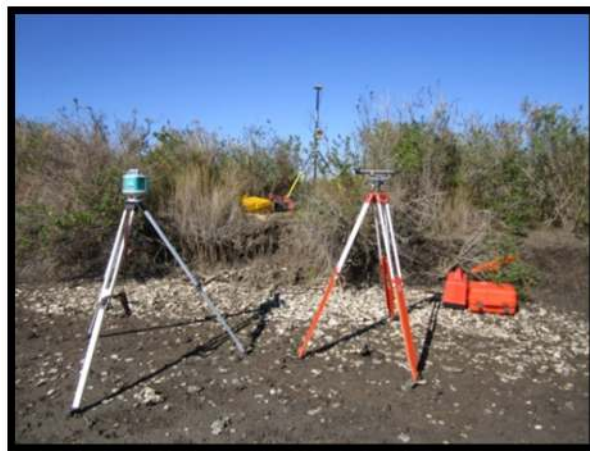


Figure 4.4: TopCon GRS-1 GPS unit, laser level, and “dumpy” level survey

4.3.3 Bathymetry Profiles

Laser level transects were recorded throughout the study period on three different reefs that were emplaced over different periods of time (see Figure 4.6). Each reef was monitored from the shoreline to the seaward side using a series of grid-pattern survey transects. These transects were used to estimate sediment accretion over time. Monitoring low-bearing pressure soils for

sediment accretion, scour, and structure settlement can be very challenging. Proper and consistent techniques must be used in order to obtain accurate and quantifiable data.

4.4 Results

Sediment accretion behind breakwater structures was surveyed, measured, and observed. The results indicate significant sediment accretion behind the existing heavy emplacement as compared to baseline/control conditions of adjacent, unaffected shorelines. Less accretion was observed on the recent emplacements as compared to a baseline reference site. No sediment accretion was measured on the solo ring structures as compared to baseline reference site conditions.

Structure settlement was also surveyed and observed. The initial, instantaneous settlement of the ring structure could have been as much as two inches. Little, if any, actual settlement was surveyed or observed after initial placement. Increased settlement could occur due to scour around the ring structure caused by wave forces, especially on end units. End units seemed to be most susceptible to this scour settlement effect and exhibited visually observable tilting.

Scour was observed on all structures, especially near the end units. This scoured sediment could have contributed to the leeward sediment deposition and accretion. In some cases, scour was severe enough to actually tilt the concrete ring structure. By observation, ring structures with portal holes exhibited less scouring due to an increase in wave energy absorption within the structure. Scouring may also be prevented by placing rings on a geotextile mattress or membrane. Depending on their composition, the inclusion of mats could lead to an increase in oyster recruitment and overall functionality of a nearshore detached intertidal breakwater serving as an artificial oyster reef.

4.4.1 Pilot Scale Emplacements

Figure 4.5 below, shows three new reef installations as segmented breakwaters. The ring configurations were placed within the intertidal zone along a canal of St. Johns Bayou in Rockefeller Wildlife Refuge.



Figure 4.5 a, b, c: Initial ring-reef emplacements with (a) heavy, (b) light, and (c) solo rings.

The heavy emplacement contained 14 rings, while the lighter emplacement contained four rings and several concrete logs. The solo emplacement contained individual rings of slightly different geometries to evaluate field strength, scour and “tipping” under low-energy wave conditions.

4.4.2 Sediment Bathymetry Surveys

Sediment Bathymetry surveys were taken using a Sokkia LP30A. It is difficult to measure the amount of sediment with common survey techniques, given the soft clay composition of the sediments. A method was used that involved placing a bearing plate down and then placing the grade rod on top of the settled bearing plate. This method proved to be the most accurate and consistent way to measure sediment within the system.

The figure below shows a sediment bathymetry survey schematic on an existing pilot reef at Rockefeller after several years of emplacement. This sediment survey was conducted to establish long-term accretion rates to compare to newer pilot reef bathymetry surveys.

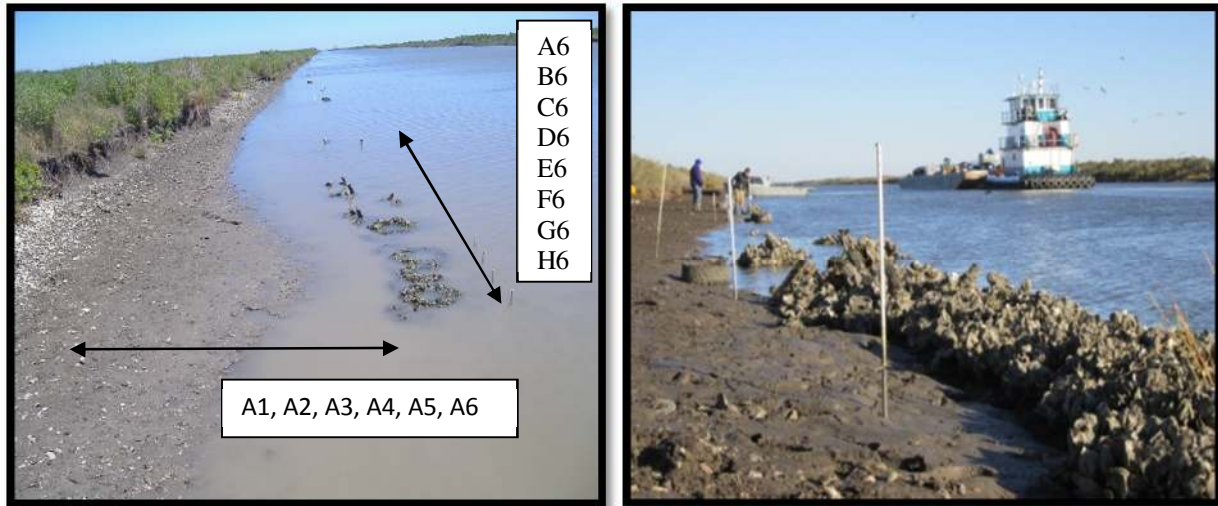


Figure 4.6 a, b: Existing reef (Site 1) sediment salient effect behind breakwater structure.

Reference bathymetry surveys were also established on undisturbed shoreline features near the project site. Tabular bathymetry survey transects calibrated to AMSL are presented in Table 4.3-1 below. Site 1 is an existing reef that has exhibited significant sediment accretion over time, as seen in the figure above. The tabular results in Table 4.1 depict a calibrated grid bathymetry survey to AMSL as established by the GPS benchmark. Cross-shore transects were measured from the shoreline to the leeward side (longshore) of the reefs and adjusted in relation to the established sea level benchmark. The square meter grid transects were used to calculate volumetric accretion rates when compared to control and baseline conditions.

Table 4.1: Tabular sediment survey data (in meters) AMSL at Site 1. Local Reference at 1.672 AMSL (Wolcott, 2011)

Site 1	A	B	C	D	E	F	G	H
1	0.16	0.15	0.19	0.19	0.18	0.16	0.19	0.14
2	0.07	0.05	0.14	0.19	0.14	0.04	0.11	0.12
3	-0.06	-0.07	0.08	0.09	0.07	-0.07	0.03	-0.01
4	-0.21	-0.16	-0.11	-0.11	-0.17	-0.26	-0.11	-0.23
5	-0.39	-0.36	-0.39	-0.39	-0.39	-0.51	-0.39	-0.39
6	-0.55	-0.52	-0.52	-0.52	-0.49	-0.54	-0.61	-0.52

The transects measured revealed 3.92 m³ of sediment accretion behind this reef, which was emplaced in 2007. The newly emplaced reef configurations summarized below consisted of a heavy and light emplacement of 14 and four rings placed in a 10-foot segmented breakwater configuration. Tabular transect summaries for Site 3-H and Site 3-L are summarized in Table 4.3-2.

Table 4.2 a, b: Tabular sediment survey data (in meters) AMSL at Site 3H and 3L

Site 3-Heavy	A	B	C	D	E	Baseline	Control 1
1	0.11	0.10	0.15	0.15	0.16	0.11	0.11
2	0.06	0.03	0.07	0.09	0.07	0.02	-0.01
3	-0.02	-0.06	-0.04	-0.02	-0.02	-0.09	-0.14
4	-0.13	-0.19	-0.14	-0.15	-0.18	-0.22	-0.29
5	-0.27	-0.29	-0.36	-0.36	-0.31	-0.42	-0.42
6	-0.41	-0.43	-0.47	-0.49	-0.41	-0.58	-0.56

Table 4.2 continued.

Site 3-Light	A	B	C	D	E	Baseline	Control 1
1	0.15	0.17	0.15	0.17	0.17	0.11	0.11
2	0.07	0.07	0.07	0.07	0.09	0.02	-0.01
3	-0.02	-0.05	-0.02	-0.05	0.00	-0.09	-0.14
4	-0.13	-0.16	-0.16	-0.17	-0.10	-0.22	-0.29
5	-0.24	-0.28	-0.32	-0.36	-0.27	-0.42	-0.42
6	-0.41	-0.34	-0.44	-0.47	-0.44	-0.58	-0.56

Sediment accretion volumes behind these two reefs were estimated at 2.65 and 2.14 m³ when compared to baseline reference conditions. Sediment accretion rates varied among all reefs, which can be attributed to the timing and size of emplacement. Subsequent years, likely accompanied by increased biological growth, exhibited the most visible sediment accretion, forming a salient response. Newer reefs will need to be monitored into the future to fully understand variable accretion rates behind the different type of breakwaters installed. The three reef configurations' sediment accretion rates over time are graphically summarized below

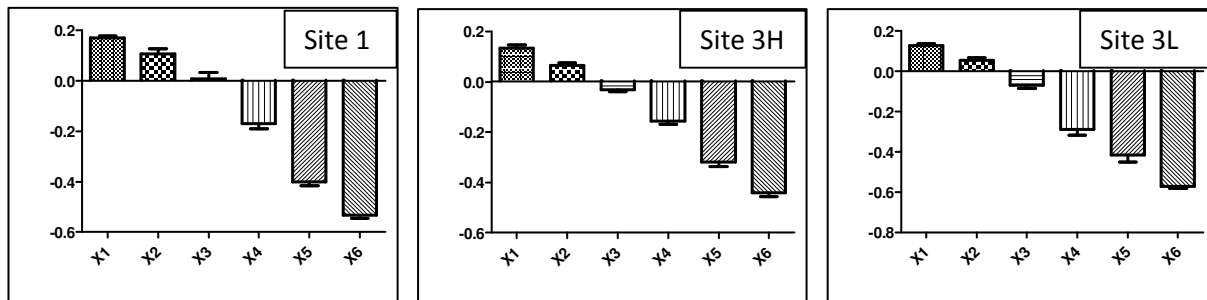


Figure 4.7: Sediment column graph transects (in meters AMSL) showing significant differences in all transects at each site (ANOVA, P < 0.001).

The figures above show predicted leeward sediment accretion over time on different reef configurations. The data allows one to hypothesize that this sediment accretion can be manipulated given different ring composite structures and configurations. Extreme storm events may exacerbate this sediment effect, or simply overburden the reef structures with sediment. However, existing pilot reefs have withstood numerous hurricane events within the past several years and remain viable.

4.4.3 Settlement and Scour

Biologically dominated engineered coastal breakwaters can offset land subsidence and structural settlement. These reefs can experience a settling effect due to overall mass, similar to traditional rock breakwaters. Traditional rubble-mound breakwaters can experience extensive settlement over time, which limits long-term effectiveness of the structure, and creates engineering and economic implications. Because biologically dominated engineered coastal breakwaters have a lighter mass, they experience less instantaneous settlement effects, and therefore, the overall settlement over time is offset by the biological growth. This factor, along with the biologically attractive nature of the structures, can lead to long-term effectiveness as a detached breakwater structure, as well as providing continued multiple lines of protection from hurricane events.

Figure 4.8 below shows an alternate emplacement of six rings utilizing a geotextile mattress base to prevent settlement and scour. Survey results are also tabulated below in Figure 4.8.

Depending on site soil conditions and hydrodynamic forces, an artificial concrete ring reef (and individual rings) may experience scouring effects that displace bottom sediment and compromise the stability of the ring. Height to width ratios of individual rings should be considered in design scenarios to prevent tipping and rolling.



Site 4-M	A	B	C	D	E
1	0.05	-0.02	-0.02	-0.02	-0.02
2	-0.07	-0.08	-0.09	-0.09	-0.11
3	-0.27	-0.21	-0.23	-0.24	-0.30
4	-0.38	-0.32	-0.32	-0.35	-0.46
5	-0.60	-0.46	-0.44	-0.45	-0.59

Figure 4.8 a, b: (a) Six-ring emplacement with geotextile fabric liner and (b) Tabular sediment survey data (in meters) AMSL at Site 4-M

Additionally, geotextile fabrics can underlay the reef to preclude such effects. During the pilot demonstration project, one of the taller rings was compromised by scour; it tipped and then rolled into the lower depths of the canal. This solo ring emplacement initially experienced exceptional oyster spat settlement and growth; however, once it moved lower in the intertidal zone, the oysters were subject to increased predation and biofouling.

Currently, these breakwater structures are purportedly 1/3 the weight of traditional rock breakwaters and incur an instantaneous settlement of approximately four inches. The goal is to minimize the composite structure weight to reduce instantaneous settlement and settlement over time, thus increasing the lifespan of the structure. Reducing structure settlement and maximizing biological growth enhance the ability of a breakwater to dissipate wave energy and to promote sediment accretion over time, thereby providing a sustainable living shoreline for coastal protection.

4.5 Discussion and Conclusion

Sea level rise, a lack of system sediment supply, and land subsidence are factors magnifying coastal erosion on the Louisiana Gulf Coast. Rock breakwaters are the typical defense mechanism employed to prevent coastal erosion by reducing wave energy and promoting sediment accretion. In this experimental pilot study, field surveys showed that biologically dominated artificial breakwater reefs can promote sediment accretion and protect the shoreline, while promoting biological growth. Oyster growth on these reefs can offset environmental conditions such as sea level rise and allow for a viable method of coastal shoreline stabilization and restoration. These reefs also provide environmental and engineering benefits, as well as multiple lines of protection for coastlines and ecological communities.

Bioengineered oyster reefs were deployed as a pilot study in Rockefeller National Wildlife Refuge as biologically dominated engineered detached breakwater systems. These systems were subsequently monitored for sediment accretion using bathymetry profiles obtained through surveys and GPS systems. The results show an increase in sediment accretion over time, likely due in part to the biological growth on the breakwater structure. Pilot scale breakwater emplacements dominated by biological growth accumulated nearly 4 m³ of sediment over four years. Heavy and light emplacements installed for less than one year accreted 1.6 and 0.37 m³ of sediment, respectively. These biologically dominated breakwater structures serve as three-dimensional artificial oyster reefs and provide shoreline protection against coastal erosion. These reefs may prove a viable alternative to traditional breakwater structures, especially when the design is optimized to maximize ecological benefits and reduce installation and maintenance costs. The use of these types of reefs as a living shoreline is gaining more attention in Louisiana

as coastal engineers and scientists search for a sustainable environmental shoreline protection methods for coastal restoration.

4.6 Summary and Future Work

Bioengineered breakwaters can improve water quality, dissipate wave energy, and promote sediment accumulation, as well as provide biologically enhanced aquatic environments and ecosystems. Future work should continue monitoring existing reef bathymetry profiles relative to calibrated temporary benchmarks. These reefs should be evaluated for long-term sediment accretion rates and impacts to sediment accretion from biological growth. Additional research should also be conducted on structure settlement and scour, and how these variables impact sediment accretion rates behind biologically dominated artificial reef structures. A sediment balance within the entire system could contribute to a better understanding of performance.

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CHAPTER 5: COASTAL ZONE MANAGEMENT FOR BIOLOGICALLY DOMINATED ENGINEERED BREAKWATER REEFS

Louisiana is experiencing significant land loss in the coastal zone, due to many natural and anthropogenic factors. Shoreline protection is now becoming a focus of coastal zone managers, scientists, and engineers within the region. Sustainable, viable, biological solutions are being explored, including the use of artificial breakwater structures that become biologically dominated by oyster growth. These living shorelines reduce land loss and promote sediment accretion by diffusing wave energy as it passes along the reef. They can also accommodate some land subsidence and sea level rise with adaptive oysters growing vertically on reefs in the intertidal zone. The biological growth on these breakwater reefs also contributes many other ecosystem services such as water quality improvement and carbon sequestration. The use of these biologically dominated breakwater structures may prove a viable solution for shoreline protection in Louisiana.

5.1 The Louisiana Coastal Zone

The coastal zone of Louisiana contains a wide variety of intercoastal waterways, canals, estuaries, and marshland. The vast area of the Louisiana coastal zone is depicted in Figure 5.1 below. This area is extremely vulnerable to land loss due to many factors, such as subsidence, sea level rise, hurricanes, oil and gas development, and dredging. Oyster reefs were once predominant in the intertidal zone and helped offset some coastal erosion. High-relief, three-dimensional oyster reefs provide many ecosystem services, including water filtration, habitat, and carbon sequestration potential.

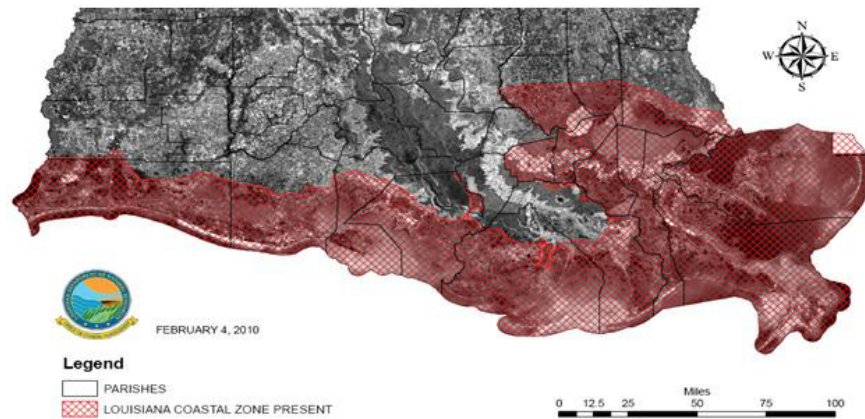


Figure 5.1: The Louisiana Coastal Zone (OCPR, 2010)

Land subsidence has increased with the depressurization of sub soil conditions from oil and gas production and oil spills that demolish marine grasses, kill marine wildlife, and erode marshes (Ko and Day, 2004). Large-scale water management projects that were created beginning in the early 20th century to prevent flooding along the Mississippi River delta have been successful in reducing flooding, but have also deprived wetlands and barrier islands of the sediment and the nutrients they need to sustain them (CPRA, 2008; Wilkins et al., 2008). Furthermore, climate change constitutes additional threats, as sea level rises in the Gulf of Mexico and inundates low-lying marshes, increasing the salinity in naturally freshwater or brackish areas. In watersheds hundreds of miles up the Mississippi River, there are extreme rainfall trends, which also have varying effects on sediment dispersion (Twilley, 2007). Hurricanes also destroy the wetlands of

Louisiana, contributing to land loss. In 2005, Hurricanes Katrina and Rita destroyed approximately 217 square miles of wetlands (Schleifstein, 2011).

5.1.1 Coastal Breakwaters

Hard armoring structures such as rock breakwaters are commonly used to mitigate coastal erosion, but these structures lack a viable biological component needed to facilitate ecological recovery and often cause undesirable effects such as increased erosion of adjoining shoreline, loss of the extremely productive intertidal zone, and continued fiscal drain from the perpetual maintenance such structures require.

Coastal breakwaters can be used to form artificial reefs that become biologically dominated over time, promoting sediment accretion and sheltering coastlines from wave energy. Bioengineered artificial oyster reefs are one possible tool to mitigate coastal erosion problems in the Louisiana coastal zone. These reefs could be used for protecting shoreline and barrier islands and are designed to reverse erosion and resist both storm surge and sea level rise. Using oyster reefs as a natural shoreline protection can minimize the destructive force of waves before they have the chance to reach the shore (Master Plan, 2012). The biological growth on these structures can offset traditional breakwater design constraints by achieving sustainable three-dimensional, high-relief vertical growth. Oysters were once valued primarily as a fishery resource, but today increasing attention is being focused on other ecosystem services that oysters and their reefs provide in coastal bays and estuaries (TNC, 2011; Brumbaugh and Coen, 2009). Oyster reefs can increase ecosystem recovery by filtering water, sequestering carbon, and providing habitat.

5.1.2 Sea Level Rise Impacts on Louisiana Coastal Resources

The International Panel on Climate Change (IPCC) estimates that the global average sea level will rise between 0.6 and 2 feet (0.18 to 0.59 meters) in the next century, which may be considered conservative in the Gulf coast region. In the last century, relative sea level rose 5 to 6 inches more than the global average along the Gulf because these coastal lands are subsiding (IPCC, 2007). Sea level rise and subsidence cause land loss that may not be effectively managed by a traditional detached breakwater system. The use of biologically dominated breakwater systems that become three-dimensional oyster reefs may offset land loss impacts caused by sea level rise and subsidence. These structures become living breakwaters that may protect, restore, or even create shorelines. The biological growth over time increases the capacity of the breakwater to attenuate wave energy and buffer land loss.

5.1.3 Regional Sediment Management in the Coastal Zone

The concept of Regional Sediment Management (RSM) derived from the U.S. Army Corps of Engineers (USACE) is related to conservation and management of sediments in the littoral zone and attempting to “design with nature,” by utilizing an understanding of sediment movement in a region and the interrelationships of projects and management actions for ecosystem restoration and protection (Martin, 2002). Sediment resources that are a part of a regional system involving natural processes have a significant impact on the ability to restore and sustain coastal habitats (Khalil et al., 2011). Mississippi River diversions are one way to reintroduce sediment within the coastal zone. Large-scale freshwater diversions have been operating in Louisiana for many years, but these diversions are now being evaluated for their potential to restore marshes and wetlands, as well as oyster public seed grounds. Large-scale and small-scale freshwater

diversions and combinations of both can be used for coastal protection and restoration (Martin, 2002). Bioengineered oyster reefs serving as intertidal coastal breakwaters provide a viable tool for coastal zone managers by combining science and engineering to mitigate coastal erosion and to facilitate ecological recovery while supporting public oyster seed grounds.

5.1.4 Bioengineered Artificial Oyster Reefs

The channelization of the Mississippi River has altered native ecosystems and caused some land loss in coastal Louisiana by cutting off the supply of sediment-rich river water that inundated the land during seasonal flooding. The tactical deployment of new freshwater diversions has been modeled, but the effects of impacts and first flush phenomena are yet to be determined, as the natural environment will respond to these alterations in flow regimes and eventually reach a new state that may or may not be stable over time. Oysters will likely be closely monitored in response to these new flow regimes and associated salinity fluctuations. The use of bioengineered oyster reefs in these diversion areas will be a focus of additional study to determine their efficacy as breakwater structures to trap sediment and promote land accretion.

The use of biologically dominated breakwater structures allows for a potential ecologically beneficial method of shoreline protection while offering additional ecosystem services. Further, these engineered structures can biologically adapt to sea level rise and water quality fluctuations. Pilot scale experimental concrete reefs have been deployed at the Rockefeller Wildlife Refuge, as seen below, to provide a scaffold for oyster growth that enhances the effectiveness of the intertidal breakwater system when biologically dominated.



Figure 5.2 a, b: Rockefeller pilot bio-breakwater experimental reef (2012)

Artificial oyster reefs can also support public oyster seed grounds by serving as marine broodstock sanctuaries supplying millions of larvae each year that will grow to harvestable size within several years.

5.2 Coastal Zone Management—Regulatory Environment and Agency Involvement

Kamphuis (2010 a and b) notes that coastal management is integrally related to coastal engineering practice and must be included in any discussion about the future of coastal engineering. Ecosystem-based management requires the integration of multiple system components and uses and identifying and striving for sustainable outcomes (Boesch, 2006). Sustainability includes a long-range concern for the future to generate self-sustaining improvements in human capability and well-being; and biological diversity conservation is an urgent coastal matter (Clark, 2006). In ecology, sustainability describes how biological systems

remain diverse and productive over time. This implies incorporating nature with design for viable coastal restoration and shoreline protection.

The following is a listing of state administrative agencies and their regulatory responsibilities.

The agencies have the potential to affect the use of bioengineered reefs in Louisiana coastal areas by either limiting or promoting their use.

5.2.1 Louisiana Department of Natural Resources (LDNR), Office of Coastal Management (OCM)¹

In 1972, the federal government gave the individual states the ability to establish their own Coastal Management Programs under the Coastal Zone Management Act (CZMA), based on federally mandated criteria. In response to the CZMA, Louisiana established the State and Local Coastal Resources Management Act, which created the Louisiana Coastal Resources Program (LCRP). The Louisiana Department of Natural Resources Office of Coastal Management (OCM) is the agency that implements the LCRP through two organizational divisions. The OCM also establishes and administers the Coastal Use Permitting program, which regulates a variety of activities within the coastal zone that may have a direct and significant impact on coastal waters.

5.2.2 Louisiana Coastal Protection and Restoration Authority (CPRA)²

In December 2005, the Louisiana Legislature restructured the state's Wetland Conservation and Restoration Authority to form the Coastal Protection and Restoration Authority (CPRA)². The CPRA was to develop and implement a comprehensive coastal protection plan, including both the Master Plan (revised every five years) and annual plans. The CPRA considers both "hurricane protection and the protection, conservation, restoration, and enhancement of coastal

¹ <http://dnr.louisiana.gov> (last visited May 30, 2012)

² OCPR <http://coastal.louisiana.gov/> (last visited May 30, 2012)

wetlands and barrier shorelines and reefs.” The State Office of Coastal Protection (OCPR), located in Baton Rouge, was also created to carry out the policies of the CPRA and to implement the Master Plan.

5.2.3 Louisiana Department of Wildlife and Fisheries (LDWF)³

The Louisiana Department of Wildlife and Fisheries (LDWF) Marine Fisheries Division manages oysters on the public grounds. The state also maintains large acreages of waterbottoms that are designated as public oyster seed grounds. This includes placement of cultch materials ranging from shells, limestone rock, and crushed concrete that increase oyster settlement/recruitment and foster the aquaculture community. The LDWF oversees commercial applications of such cultch material and administers contracts and project oversight. LDWF also oversees artificial reef construction. By combining oyster reef recovery with coastal restoration programs, viable sustainable solutions may emerge for coastal zone managers that are acceptable to scientists and engineers alike. Not to mention the potential larvae dispersal to public seed grounds.

The Louisiana Artificial Reef Program (LARP) was established in 1986 to take advantage of obsolete oil and gas platforms, which were recognized as providing habitat important to many of Louisiana's coastal fishes. In 1999, the LARP created the world's largest artificial reef from the Freeport sulfur mine off Grand Isle. The reef program has also developed 29 reefs in Louisiana's inshore waters, primarily low-profile reefs composed of shell or limestone. Eight inshore artificial reefs have been constructed using Reef Balls™. These concrete modular units provide settling surface for oyster spat, which grow quickly under optimal environmental conditions.

³ <http://www.wlf.louisiana.gov/fishing/artificial-reef-program> (last visited May 30, 2012)

Oysters and have proven effective in wave attenuation and sediment accretion. The dual effects of oyster reef restoration and shoreline protection provide a viable solution to satisfy both biological and engineering perspectives on projects. This may be the case with the use of bioengineered artificial reef systems as a new method to accomplish this department's goals.

5.3 Planning and Funding for Bioengineered Oyster Reef Projects⁴

As previously discussed, there are many state and federal agencies involved to ensure project implementation and success, placing an emphasis on multidisciplinary approaches to successful project planning and delivery. These planning efforts call for sustainable, ecological, and socioeconomic efforts for coastal restoration and shoreline protection. Biologically dominated coastal breakwaters can be integrated into coastal zone management strategies to preserve coastal resources by offering compatible uses across multiple disciplines. Further, these structures are supported by planning and funding efforts and can fit into existing regulatory guidelines and legal requirements.

5.3.1 Coastal Wetlands Planning Protection and Restoration Act (CWPPRA)

Louisiana's primary coastal management mechanism is the State and Local Coastal Resources Management Act as discussed in the previous section. Coastal restoration and engineering is primarily directed by the Coastal Wetlands Planning Protection and Restoration Act (CWPPRA, or the Breaux Act) and the Office of Coastal Protection and Restoration.

Louisiana receives approximately \$50 million each year for coastal restoration projects funded by CWPPRA. CWPPRA recognizes the importance of habitat restoration and sustaining

⁴ <http://coastal.louisiana.gov/> (last visited May 30, 2012)

communities that enhance the economic uses that raise the value of the region. CWPPRA-funded vegetative planting, river diversion, hydraulic restoration, marsh creation, shoreline protection, sediment trapping, and barrier island stabilization are many of the techniques that are employed to rebuild and protect the coastal wetlands. Several biologically dominated shoreline protection demonstration projects have been funded through CWPPRA and have long-term monitoring components to evaluate the continued effectiveness of sustainable measures implemented in the coastal zone. The use of bioengineered oyster reefs for shoreline protection will likely receive additional future funding under the CWPPRA program once these demonstration technologies have been proven on a large scale.

5.3.2 Coast 2050

Coast 2050 is a multidisciplinary approach to develop and implement a strategic coastal plan for Louisiana's coastal zone and its valuable natural resources. The plan involves the collective effort of various federal, state, and local agencies, as well as parish governments, landowners, environmental groups, industry, recreational and commercial fisherman, and concerned citizens.

The goal of the Coast 2050 initiative is to develop a technically sound strategic plan to sustain coastal resources and to provide an integrated multiple use approach to ecosystem management in partnership with the citizens of Louisiana. Regional strategies identified in the Coast 2050 Plan include large-scale river diversions, maintenance of the integrity of major shorelines, barrier island restoration and maintenance, and restoration of natural watershed drainage patterns. This report summarizes a strong support for sustainable ecosystem restoration services needed in coastal Louisiana. Coast 2050, conceptually, has now been combined into the Louisiana Coastal Area Ecosystem Restoration Plan, discussed below.

5.3.3 Louisiana Coastal Area (LCA) Ecosystem Restoration Plan⁵

The LCA, based in part on Coast 2050, was the first step in putting into effect the restoration strategies to protect the coast of Louisiana. The original goal of this study was to develop a comprehensive plan for implementing the regional ecosystem restoration strategies identified in the Coast 2050 report. The near-term plan for the first 10 years includes funding for demonstration projects. The LCA Plan emphasizes the use of restoration strategies to achieve a sustainable coastal ecosystem that can support and protect the environment and the socioeconomic interests in coastal Louisiana. So, the LCA would seem to support the concept of bioengineered oyster reefs for shoreline protection and ecological restoration.

5.3.4 The Louisiana 2012 Master Plan

The CPRA updates Louisiana's Comprehensive Master Plan for a Sustainable Coast, (hereafter Master Plan) every five years. The 2012 Master Plan has just been published and proposes restoration projects that would cost \$50 billion, nearly \$15 billion of which is slated for non-structural shoreline protection and other restoration programs. The 2012 Master Plan final draft has been publicly reviewed and submitted to the Louisiana Legislature for approval. The 2012 Master Plan calls for bioengineered oyster reefs to "improve oyster propagation and serve as breakwaters to attenuate wave energies" and identifies two specific projects:

- East Vermilion Bay Oyster Barrier Reef Restoration: Oyster barrier reef in the vicinity of Dead Cypress Point \$20.99M 03b.OR.02
- West Vermilion Bay Oyster Barrier Reef Restoration: Oyster barrier reef in the vicinity of Marone Point \$22.54M 03b.OR.03

⁵ <http://www.mvd.usace.army.mil/lcast/index.html> (last visited May 30, 2012)

**Distribution of Funding by Project Type
(Approximately \$50 billion)**

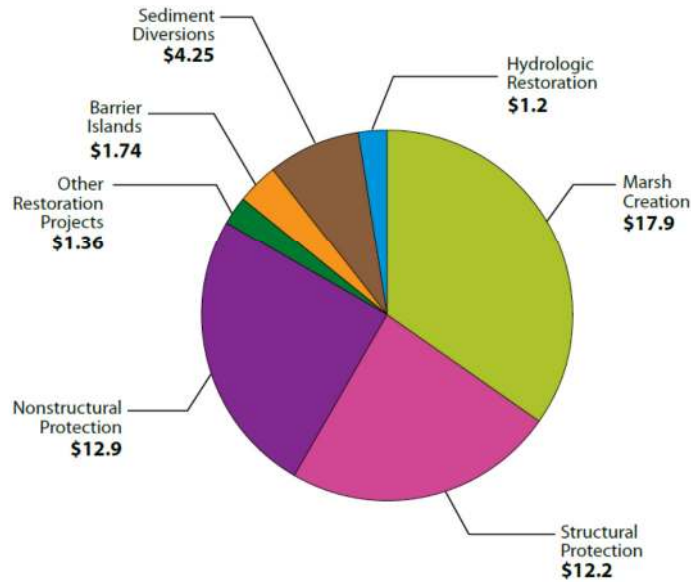


Figure 5.3: Distribution of funding by project type (Master Plan)

The Master Plan emphasizes the use of natural processes for restoration along the coast. This includes land building and shoreline protection by oyster reefs. Further, to predict changes in oyster habitat, the Master Plan also emphasizes a habitat suitability index to account for land change and water, and bottom characteristics.

5.3.5 Coastal Impact Assistance Program (CIAP)⁶

The Energy Policy Act of 2005 established the Coastal Impact Assistance Program (CIAP), which authorizes funds to be distributed to oil and gas producing states for the conservation, protection, and preservation of coastal areas, including wetlands. The source of these funds is authorized from the Outer Continental Shelf (OCS) Lands Act, as amended; 31 U.S.C. 6301-

⁶ <http://wsfrprograms.fws.gov/subpages/grantprograms/CIAP/CIAP.htm> (last visited May 30, 2012)

6305. Federal grant funds must be used to directly benefit an authorized use to conserve, restore, enhance, and protect renewable natural resources. Non-federal matching funds are not required for approved grant projects associated with this federal grant program. Under the CIAP, these funds will be shared among Alabama, Alaska, California, Louisiana, Mississippi, and Texas. In 2011, CIAP management was transferred from the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE) to the U.S. Fish and Wildlife Service (FWS). The use of biologically dominated breakwaters serving as high-relief oyster reefs provides a valuable and viable tool for coastal restoration and shoreline protection and could be considered for potential CIAP funding.

5.3.6 Gulf Coast Research Initiative (GRI)⁷

The Gulf of Mexico Research Initiative (GRI) was created on May 24, 2010, to distribute money donated by BP for oil spill research in the Gulf of Mexico. BP committed \$500 million over a 10-year period. The GRI is a broad, independent research program that will be implemented at research institutions, mostly in the states bordering the Gulf of Mexico.

The GRI Master Research Agreement (GRI MRA) was formed between BP and the Gulf of Mexico Alliance (the Alliance is a non-profit organization that consists of the governors of the five Gulf coast states). The GRI MRA establishes the structure of the GRI, and it deals with the selection and distribution of grants from the GRI.

The GRI has many purposes; it primarily investigates the impacts of dispersed oil on the environment of the Gulf of Mexico and the Gulf coast states. The GRI also aims to improve the

⁷ http://gulfofmexicoalliance.org/pdfs/Gulf_of_Mexico_Research_Initiative_Master.pdf (last visited May 30, 2012)

understanding of the dynamics that are associated with these events, such as environmental stresses and public health implications. The GRI seeks to fund research that will improve spill mitigation, oil and gas detection, characterization, and remediation technologies. The GRI's main goal is to help the public understand the impacts of petroleum pollution and related hazards to the marine and coastal ecosystems in the Gulf of Mexico. The GRI is an independent scientific research program and is separate from the Natural Resources Damage Assessment process.

5.3.7 Natural Resource Damage Assessments (NRDA)

The 1990 Oil Pollution Act (OPA) requires that a Natural Resource Damage Assessment (NRDA) be conducted to determine the type and amount of restoration needed to compensate the public for harm to natural resources and their human uses that occur as a result of an oil spill.

One of the steps within the NRDA process is to identify potential restoration ideas that will then be evaluated within a Damage Assessment and Restoration Plan (DARP). The National Oceanic and Atmospheric Administration's (NOAA) Damage Assessment Remediation and Restoration Program (DARRP) is coordinating this effort for the Macondo (BP) oil spill that occurred in the summer of 2010, with natural resource trustees in four states (Louisiana, Mississippi, Alabama, and Florida), along with additional project oversight provided by the U.S. Fish and Wildlife Service (USFWS). Multiple agencies from each state are engaged in the process to determine specific recovery projects.

Bioengineered oyster reefs provide a mechanism to achieve multiple benefits and seem consistent with the NRDA/DARP planning process. These reefs not only protect shorelines, but also offer many other ecosystem services that will likely facilitate recovery from the BP oil spill,

including socioeconomic benefits in nexus with oyster harvest, public seed grounds, and the aquaculture industry.

5.3.8 Funding Mechanisms through Non-Profit Entities

The Nature Conservancy (TNC) is a proponent of the use of bioengineered artificial oyster reefs to facilitate shoreline protection and mitigate land loss, as these structures seem to provide a sustainable solution for coastal restoration efforts in the Gulf of Mexico. TNC has sponsored several demonstration projects to evaluate the potential use of these structures and the additional ecological benefits offered. One program utilized grant monies from the Department of Commerce Recovery Act for approximately 3.4 miles of shoreline at three sites in Jefferson Parish and two sites in St. Bernard Parish. Another program in Vermilion Parish is discussed below.

5.4 Permitting an Artificial Oyster Reef Breakwater Project

All shore protection projects that will affect navigation must apply for and receive a permit from the U.S. Army Corps of Engineers (USACE) prior to construction. This permit is pursuant to Section 10 of the Rivers and Harbors Act (1899). In addition, if the project will involve the deposit of dredged or fill material into the navigable waters of the United States or result in accumulation of sediment in those waters, a permit will be required under Section 404 of the Clean Water Act (1972). The Section 404 permit process considers and evaluates many factors, including effects on conservation, economics, aesthetics, general environmental concern, wetlands, cultural values, fish and wildlife resources, flood hazards, flood plain usage, land use, navigation, shore erosion and accretion, recreation, water supply and conservation, water quality, energy needs, safety, food and fiber production, mineral needs, and the welfare of people and

society. Louisiana has a Joint Permit Application process for local boards, state agencies, and the USACE permit. This method saves considerable expense and time in that only one permit application is required for all three levels of government review of the proposed project.

5.4.1 Coastal Use Permit for Work within the Louisiana Coastal Zone

The Coastal Use Permit (CUP) is the principal regulatory tool to control any project within the coastal zone deemed to have a “direct or significant impact to the coastal waters of Louisiana.” Anyone performing such an activity must apply for a CUP. The permit process allows for inter-agency review and public comment. Generally, the CUP consists of a 16-step process including relevant information on applicant, agents, landowners, purpose, status, impacts, public notice, fees, and certification. The second part of the application entails providing maps and drawings of the proposed project. This application is also forwarded to the State Lands Office for processing.

5.5 Case Studies

5.5.1 Bioengineered Oyster Reef Demonstration Project (Vermilion Parish)

The Nature Conservancy’s Vermilion Parish demonstration project was funded by the National Fish and Wildlife Foundation's Shell Marine Habitat Program. Approximately 350 concrete module units of OysterBreak™ rings manufactured by Wayfarer Environmental Technologies (WET) were placed in the intertidal zone waters located near Southwest Pass in Vermilion Bay. This project employed multiple treatment scenarios comparing different concrete mixtures, emplacements, and design scenarios. This project was completed in June 2010, and it is

monitored by the LSU School of Renewable and Natural Resources for shoreline effects, oyster growth, and biological utilization.

Large shallow-draft barges fitted with cranes placed the singular concrete modular units within the intertidal coastal zone, conforming to breakwater system design conditions. Localized subsurface soil conditions were analyzed, along with tide, wind, and water wave data to optimize design. This area has suffered from significant land loss, oyster reef loss, and habitat loss over the past century. More recently, freshwater diversions made in an attempt to mitigate the effects of the 2010 oil spill and 2011 flooding have further affected the environmental conditions for oyster growth and plant growth. This demonstration project focused on habitat restoration in a low-wave energy scenario.



Figure 5.4: Vermilion Bay breakwater demonstration project

The Vermilion Bay bioengineered oyster reef emplacements are in lower energy zones when compared to the Rockefeller project discussed below, and used four treatment scenarios to

facilitate biological and ecological activity with secondary breakwater effects where low- and high-crested breakwaters, as well as gap spacing on segmented systems, are being tested.

5.5.2 Bioengineered Oyster Reef Demonstration Project (Rockefeller Refuge)

The Rockefeller Wildlife Refuge project, funded by CWPPRA, consisted of protecting approximately 1,000 linear feet of Gulf shoreline with OysterBreak technologies using grid configuration. The emplacement is 34-feet wide and constructed of approximately 1,700 concrete modular units (see Figure 5.5 below). A key advantage in this application is that it overcomes extremely poor geotechnical conditions and is exposed to high-energy wave action. The structures' bearing pressure is reduced to 284 psf by installing the units on top of a marine geotextile mattress. Again, emplacement was conducted by a shallow-draft barge and crane unit, and the project focus was shoreline protection in a high-energy wave environment.



Figure 5.5: Rockefeller breakwater demonstration project

The contractor was able to place multiple rings (up to eight per load) onto the mattress, maximizing installation time. Two types of concrete rings were installed to evaluate and determine optimal biological growth conditions. This project was completed February 14, 2012, and will be monitored by NOAA and other state agencies. This is the second commercial scale project completed within the Louisiana coastal zone to evaluate biologically dominated breakwater technologies.

5.5.3 Non-Rock Alternatives and Living Shorelines (Shark Island)

Traditional shoreline stabilization techniques typically use segmented breakwaters to capture offshore sediment sources and Mississippi River sediments diversions. Nontraditional shoreline stabilization projects typically seek to demonstrate the cost and effectiveness of alternative shore protection methods utilizing non-rock alternatives, including artificial oyster reefs that provide a biological component. These projects are installed near or on marsh shorelines to provide wave protection. Three techniques: gabion mats, concrete onshore armor units, and offshore oyster shell units have proven to be successful technologies, based on anticipated effectiveness and cost. Non-traditional biologically dominated shoreline protection techniques may require additional monitoring to better assess the effectiveness of the oyster reefs but have proven to be a viable mechanism to educate the scientific and engineering communities about the practical aspects and ecological benefits. The CWPPRA Shark Island non-rock alternative project bid solicitation provides an opportunity to install biologically dominated shoreline demonstration protection projects to further evaluate overall effectiveness of these technologies within the coastal zone.

5.6 Discussion

Traditional shoreline protection technologies include limestone rock or recycled concrete for breakwaters, jetties, and revetments; shell reefs; other artificial reefs (e.g. sunken ships); and “hard” structures like seawalls. Biologically dominated concrete structures include OysterBreak concrete rings, steel triangles filled with cultch called ReefBLK, and another comparable structure called Reef Balls. These concrete structural materials, when properly placed as breakwaters, will become biologically dominated by oysters and other organisms. Non-rock aggregates are currently being considered for some of these structures. There are also some “soft” alternatives (usually consisting of a biological component), including dredge/mud technologies (e.g. Geotubes), coastal mats (some with plants – e.g. Floating Island), and plantings (usually associated with sand or mud emplacements). The costs of traditional coastal protection methods, which include environmental impacts and other factors related to these methods, are well known to the industry. Biologically dominated coastal protection methods can provide an alternative way to protect or enhance the environment and create estuarine and marine habitat while still offering shoreline protection benefits similar to traditional hard armoring methods. Typically, these non-rock alternatives require less material, are less destructive in emplacement, and are more sustainable, especially when considering environmental factors and well-documented maintenance required for heavy, hard armoring structures that settle over time in the soft soils.

All the biologically dominated technologies have the basic limitation that they are not in their “final configuration” for some time period after installation: the oysters have to settle, grow, and survive predation, while plants have to root, grow, and survive predation and other water quality impacts. However, all biological technologies have the advantage that the structures tend to get

“better” over time, provided conditions are optimal for biological growth. These technologies dissipate more energy; become more stable; and provide more habitat, though most provide some habitat immediately.

Traditional hard engineering technologies are well-known, and contractors know how to construct them. However, rock and concrete are heavy, causing issues in emplacement (e.g. excess dredging in shallow areas), and biological growth is limited due to less surface area and sinkage of heavy materials in areas of soft muds. They are also relatively expensive in terms of mass of material emplaced per linear foot of shoreline protection. More aggressive structures like seawalls are even more expensive, requiring high strength to withstand the battering of waves, and, if overtopped, sea walls provide little additional protection or slowing of water. Then, they may even trap floodwaters in undesired areas (e.g. levees kept water in New Orleans after Hurricane Katrina) because of the low-lying lands.

Use of natural shell to form, start, or enhance reefs and/or coastal protection is becoming more common. Shell is an ideal growing material because it tends to distribute its weight along the waterbottom, exposing more surface area for oyster spat to settle and grow. However, without some additional constraint, it tends to settle, and sediment may cover it during storm events, as can be observed with abandoned crab traps and oyster cages. Additionally, oyster shell is becoming a limited commodity and may not be sustainable or even available for very large projects. Non-rock alternatives, such as vitrified clay, are becoming an increasingly interesting alternative to traditional methods. This lightweight aggregate is a material produced by expanding and vitrifying select shales, clays, and slates in a rotary kiln. The process produces a consistent high-quality ceramic aggregate that is structurally strong, physically stable, durable, environmentally inert, light in weight, and highly insulating. It is a non-toxic, absorptive

aggregate that is dimensionally stable and will not degrade over time. This porous material allows water to filter through while trapping a significant amount of suspended sediments. It also has superb phosphorous-removing properties.

“Soft” technologies include Geotubes, coastal mats, and various mud configurations. These also have a biological component and require growth before they are fully effective, with similar limitations of other biological technologies. However, muds are more erodible than products like OysterBreak or ReefBLK. Floating Island is a plant-based technology that provides some substrate and generally soft or flexible aspects allowing or encouraging plant growth.

Reef Balls have been quite successful in the surf zone and are used to promote coral growth, primarily for ecotourism and diving-type applications. They have a unique method of emplacement involving bladder-type flotation and appear quite environmentally benign. They have had limited emplacements in oyster-dominated (deltaic) systems.

“ReefBLK” is a steel-framed, oyster shell filled technology. It appears to work in a limited number of emplacements. It is solid, and the rust that appears is not a problem, as it does become biologically dominated well before it might rust through. There is evidence of plant growth behind such structures in at least one study. There are limited peer-reviewed publications on these technologies, but probably the biggest limitation will be construction cost and speed for such large-scale emplacements.

“OysterBreak” is a specialty concrete ring product, which also provides large surface areas for optimum oyster growth. It has the same limitations as all biologically dominated technologies—it takes time to grow. However, manufacture appears significantly easier due to the commercial scalability of form technologies. Emplacements of hundreds of meters of this technology are in

use, and observation has shown they become biologically dominated within about one year in most circumstances. One counterexample was an emplacement in Vermilion Bay shortly before a major flood event: this drove salinity down and reduced oyster spat set and growth. Other technologies of a similar nature would also be affected similarly by biological impacts.

Biobreakwater technologies can improve water quality, dissipate wave energy, and promote sediment accumulation, as well as provide biologically enhanced aquatic environments and ecosystems. Living shorelines and biologically dominated non-rock reef alternatives can provide multiple lines of protection against land loss in coastal Louisiana, but may face resistance from local, state, and federal agencies overseeing the process. The resistance is likely due to lack of knowledge and understanding (and limited design criteria) about the effectiveness of the breakwater systems and other value-added ecosystem services. Knowledge of coastal zone management laws and regulations is key to successful and timely project completion, and of course, securing the funding sources is crucial.

5.7 Summary and Conclusions

If the desired objective is absolute protection, perhaps no technology will suffice. High levels of protection come with costs such as high material costs, long-term maintenance costs, and impacts on the ecosystem. These high levels of protection may only be justified when, for example, a levee is needed to protect a city. In many cases, however, indirect protection of cities and infrastructure may be the most cost-effective method by using biologically based sustainable technologies. These methods generally require less initial material, but grow to become, in many cases, even more effective than traditional or hard technologies. They also offer hope for protecting or even enhancing habitat and other ecological services and values.

These methods are worthy of consideration for funding. Ongoing work on specific technologies may be necessary before their effectiveness and practicality can be determined, but preliminary work on at least three technologies suggest that each (OysterBreak; ReefBLK; and Reef Balls) will produce desired biological and hydrodynamic results. Each has certain advantages and disadvantages, generally related to manufacturing, emplacement, and growth.

Specific advantages of OysterBreak include potentially lower manufacturing costs (labor in particular), quicker emplacement, and effective biological and habitat enhancement. This product can also be more easily customized in terms of density than ReefBLK. Reef Balls have been used more in coral-dominated areas, while ReefBLK is apparently an effective method to produce a biologically dominated shoreline protection and as means of providing potentially significant local labor jobs to fabricate and install structures. The OysterBreak technology also produces local jobs but on a much larger scale.

All biologically dominated technologies depend on organism growth to establish and maintain their effectiveness and to provide other benefits. If an oil spill or other biologically damaging event or condition injures the living component, the effectiveness of these structures may be compromised. Traditional shoreline protection is based on non-biological technologies such as concrete seawalls, steel pilings, and compacted earthen levees (usually with concrete or similar top or sides as appropriate). In some of these cases, biology may only contribute as a superficial factor, such as when grass is used on levees to slow erosion. Additional demonstration projects and continued monitoring are needed to overcome the existing bias towards traditional non-biological approaches to shoreline protection and restoration.

Conversely, those who recognize the coast as a living ecosystem know that acknowledging that fact and protecting and utilizing the biological and ecological systems is a logical and efficient way to achieve multiple objectives. These objectives include erosion protection and wave reduction, as well as creating habitat for living resources such as birds and fish stocks. The devices have high levels of surface area for growth but generally have less mass, or density, per unit area, so they tend to have less impact on the surrounding ecosystem. By allowing flow-through, they enhance sediment accretion and erosion protection in a more ecologically friendly manner. Viewed in that light, the biologically dominated solutions may be preferable. In terms of initial investment and long-term maintenance costs, they may also be less costly.

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CHAPTER 6: THE FUTURE OF BIOLOGICALLY DOMINATED DETACHED COASTAL BREAKWATER TECHNOLOGIES SERVING AS ARTIFICIAL OYSTER REEFS

Bioengineered oyster reefs use lightweight aggregate mixtures with agricultural byproducts as a scaffold to attract and facilitate oyster growth. These reefs become biologically dominated, enhancing their performance as breakwaters and providing a viable tool for coastal restoration and shoreline protection. Popularity is growing among scientists, engineers, and politicians to deploy these concrete modular units in a variety of ways as a mechanism to mitigate land loss and attenuate wave energy in coastal Louisiana.

6.1 Biologically Dominated Engineered Breakwater Technologies

Bioengineered oyster reef technologies have gained considerable attention in recent years as a biological, sustainable method for providing shoreline protection with multiple benefits to the environment and ecological systems. These artificial oyster reefs perform as biologically dominated detached coastal breakwaters by attenuating wave energy and allowing sediment accretion in low-energy zones behind the structures. Over time, these structures become thriving three-dimensional oyster reefs supporting entire ecosystems in the intertidal zone while mitigating vast amounts of land loss in coastal areas. These concrete modular rings provide a scaffold for biological growth that can offset sea level rise and land subsidence and can withstand hurricane-force winds, waves, and tidal surge. The future of biologically dominated detached coastal breakwater systems serving as artificial oyster reefs is a promising as a method to provide a sustainable approach to living shoreline development within the Gulf coast.

Bioengineered oyster reefs are now being deployed as demonstration projects in Vermilion Bay and Rockefeller Wildlife Refuge, with extensive monitoring regimes focused on documenting

the long-term benefits and performance of these structures as they become biologically dominated. In 2011, Governor Bobby Jindal allocated \$60 million for Bioengineered oyster Reefs. The state's Coastal Master Plan now calls for \$40 million in Bioengineered oyster reefs for 2012, with another \$1.36 billion slated for the next 50 years for living shorelines. Natural Resource Damage Assessment (NRDA) restoration project funding from the Deepwater Horizon oil spill has yet to be distributed in Louisiana, but an estimated \$50 million per year is estimated for coastal restoration. The governor's Coastal Protection Restoration Authority (CPRA) Science and Technology Committee suggests including an oyster component in every coastal restoration project. With this type of funding allocation and political support, additional research is warranted and can be easily justified. Additional research measures include concrete cultch development for two-dimensional oyster reef development for aquaculture, lightweight concrete aggregate module units for low-bearing capacity soils, and cement additives utilizing industrial byproducts that may also attract oyster settlement on concrete structures. This type of research will likely lead to new product development and provide the scientifically engineered documentation needed for coastal zone managers in the decision-making process.

The use of coastal restoration projects to facilitate oyster recovery will also have significant and direct impacts on water quality, the environment, and socioeconomic factors. Blue carbon potential of these reefs is an emerging issue, as the oysters enter into the discussion of carbon sequestration and global carbon credits, along with the aquaculture potential of oyster reefs in Louisiana. The oyster is an ecosystem engineer and may prove to be one of the most valuable tools for coastal restoration in the Gulf of Mexico. Louisiana State University is well-positioned to continue these research efforts and to provide new insight to industry to utilize this valuable resource for ecosystem restoration.

6.2 Bioengineered Artificial Oyster Reef Technologies

Artificial reefs have been used for many years to facilitate pelagic interaction within the water column, including reestablishing coral reefs and fisheries. Until recently, artificial reefs were not utilized for oyster growth. Several technologies now focus on this specific task of creating three-dimensional oyster reefs to attenuate wave energy to reduce coastal erosion and to facilitate land accretion through sediment deposition. These reefs also have many additional environmental benefits associated with ecological restoration and carbon sequestration potential.

Existing artificial oyster reef technologies include the Reef Ball, ReefBLK, EcoDisk, and OysterKrete/OysterBreak systems that were developed through the LSU AgCenter. Advantages and disadvantages exist in material, supplies, installation, transportation, weight, and longevity of the structure to function as a three-dimensional reef. Reef Balls are hollow, holey structures traditionally employed in Florida for coral reef development. Reef Blocks are triangular units formed with rebar and filled with oyster cultch, traditionally for small-scale demonstration projects. EcoDisk claims to be the world's largest artificial oyster reef manufacturer, but most units require intensive preparation of inserting soft limestone in concrete, along with the reinforcements, and these structures have immense weight. OysterBreak technology utilizes hollow cylindrical units that are capable of being mass produced on a commercial level and are easily installed in the intertidal zone with stackable interlocking ring units serving multiple functions. Each modular unit has unique physical properties, but all have the common characteristics of providing a scaffold for oyster growth and attenuating wave energy.

6.3 Discussion

Biologically dominated engineered coastal breakwaters may provide a viable tool to mitigate coastal land loss and facilitate ecological recovery in the Gulf of Mexico. Optimizing the design of these new breakwater technologies allows sustainable measures to accommodate climate change, sea level rise, land subsidence, and hurricane events. Bioengineered artificial oyster reefs can serve as living shorelines offering many other ecosystem services by sequestering carbon and improving water quality within the coastal zone. Entire ecosystems can benefit from the biological aspects of intertidal breakwaters functioning as high-relief oyster reefs, as they can grow to become broodstock sanctuaries and supply public seed grounds with oyster larva for future harvest.

6.3.1 Oyster Biometrics

The oyster is a keystone species and an ecosystem engineer needing only a scaffold or substrate to settle and survive in most coastal zones. They are sessile, colonial, and fecund bivalves producing millions of offspring each year that settle upon existing oyster shells to form reefs. They provide many ecosystem services, including habitat and food for other aquatic organisms, water filtration, and carbon biosequestration capabilities. Oyster reefs can also dissipate wave energy, promoting sediment accretion and mitigating coastal land loss from hurricanes.

Oyster naturally form high-relief, three-dimensional (3D) reefs over time, but a significant decline in these historic reefs has led to more recent two-dimensional (2D) low-relief reefs in public seed grounds facilitated by cultch deposits for aquaculture harvest. Clam shells, oyster shells, limestone rock, and concrete have been used as cultch to facilitate oyster recovery in

public seed grounds. These low-profile reefs are less sustainable and can become silted over several years, rendering other ecosystem services obsolete.

Emplacing concrete structures as submerged intertidal breakwaters to attract oyster settlement can have an immediate influence on leeward sediment settlement rates on shorelines, as well as facilitate other ecosystem services and recovery. Further, the structural integrity of the engineered structure increases as the oysters cement themselves together. Although these 3D breakwater oyster reefs are typically not harvestable, they become oyster broodstock sanctuaries producing billions of larvae each year that could populate other 2D clutched public seed grounds for harvest.

6.3.2 Design Optimization

Bioengineered concrete can be used as scaffolds providing substrate for oyster settlement. This concrete can be produced in three-dimensional modular units and emplaced in the intertidal zone as coastal breakwaters. The biological growth on the structure over time increases its ability to function as a breakwater, facilitating sediment capture and accretion by dissipating wave energy.

Traditional breakwaters consist of limestone rock boulders placed in segments parallel to the shoreline. These traditional structures do not encourage biological growth, and the heavy material can sink in the soft soils, requiring recurrent maintenance to maintain design height. Sea level rise and land subsidence exacerbate this problem. Bioengineered concrete modular units constructed of lightweight aggregates can weigh significantly less, withstand the forces of nature, and facilitate biological growth of keystone species. These structures become biologically dominated over time, and the engineered breakwater provides an ecosystem service of a high-profile, three-dimensional oyster reef.

Biologically dominated coastal breakwater structures are engineered to reduce their total weight and to incorporate biological components to provide a sustainable solution to coastal land loss and to facilitate ecological recovery within the coastal zone.

6.3.3 Sediment Accretion

The Gulf of Mexico has experienced a dwindling sediment supply, and abundant natural land accretion is no longer being observed. Oyster reefs can potentially reduce wave energy along the coasts, but most historic 3D reefs have been lost and 2D reefs are not as effective. Breakwaters dissipate wave energy and promote sediment accretion, mitigating land loss within the coastal zone. Biologically dominated engineered coastal breakwater structures in the form of concrete modular ring units facilitate 3D biological oyster growth, thereby increasing the structures' sustainable effectiveness over time.

6.3.4 Carbon Sequestration Potential, the Blue/Green Carbon Effect

Oyster reefs have the ability to sequester carbon within an estuary system. With nutrients in the water and algal growth, oysters filter the water and feed on these organic constituents to form their shells and deposit material in the sediments. Most estuarine systems in the Gulf of Mexico could be considered substrate limited for oyster growth (as opposed to nutrient limited), as the increased amount of nutrients flowing from runoff and the Mississippi River are well documented. Oyster reefs could reduce hypoxia events by filtering nutrients in the water and consuming algae, thereby providing a net positive benefit to the global carbon biosequestration potential, or blue carbon effect.

6.3.5 Integrated Coastal Zone Management

The dwindling coastline of Louisiana has been an impetus for coastal zone management. Coastal land loss is attributed to a lack of system sediment supply, the decline of natural oyster reefs, sea level rise, hurricanes, and land subsidence. Coastal zone management covers many disciplines, including engineering, economics, science, and sociopolitical factors. Oyster reefs seem to factor well into all of these disciplines and may provide a sustainable solution to mitigate coastal land loss and facilitate ecological recovery in the Gulf of Mexico. Engineered coastal breakwaters dominated by oyster growth provide 3D structures that attenuate wave energy and provide many value-added ecosystem services when compared to traditional rock breakwaters. There could be an oyster component to every coastal protection and restoration project, as this natural ecosystem engineer serves to mitigate each factor affecting land loss in the Louisiana coastal zone.

6.4 Future Research

Future research on these biologically dominated detached coastal breakwaters is warranted and can be easily justified. Scientific and engineering studies should accumulate additional data on all technologies to evaluate long-term, sustainable methods for deployment and optimizing the use of these reefs as breakwaters and broodstock sanctuaries. Future research should focus on alternative aggregates and concrete additives, as well as cultch development to re-establish two-dimensional oyster reefs in public seed grounds promoting the aquaculture potential of oysters in Louisiana.

6.4.1 Alternate Aggregates for Bioengineered Concrete

Lightweight aggregate alternatives should be evaluated for use in these concrete modular units. Expanded vitrified clay and EcoSlag Pozzoloans are a few aggregates that could be explored. These aggregates should be evaluated in a marine environment and monitored for biological reactivity in the intertidal zone. The use of lightweight aggregates could drastically reduce transportation and installation costs, especially when emplacement occurs in low-bearing pressure soils. If the biological attractiveness of alternative lightweight aggregates proves promising, a new product could be developed through research activities and applied to industry on a commercial scale effort to provide additional coastal restoration and protection measures.

6.4.2 Concrete Alternative Additives

Concrete additives such as gypsum and fly-ash could also be utilized to reduce the costs of these modular units. Gypsum is a readily available industrial byproduct in Louisiana and could be used as an additive to cement. Gypsum may also prove to be an attractant to facilitate oyster settlement and recruitment. Fly-ash may also reduce the cost of units. With a biologically dominated unit becoming stronger over time in a marine environment, the lower strength of fresh concrete could be offset and overcome in time.

6.4.3 Cultch Development

Cultch alternatives are an area of increased research and development in Louisiana as the oyster shell becomes increasingly scarce and cost prohibitive. Agricultural byproducts could be combined with concrete to produce an oyster-like shell used as cultch. If the concrete cultch attracts oyster growth and is light enough to maintain surface area on coastal bottoms, the aquaculture industry could drastically benefit from such new product development.

6.4.4 Living Shorelines and Non-rock Alternatives

Traditional shoreline stabilization techniques typically use segmented breakwaters to capture offshore sediment sources and Mississippi River sediments diversions. Nontraditional shoreline stabilization projects typically seek to demonstrate the cost and effectiveness of alternative shore protection methods utilizing non-rock alternatives, including artificial oyster reefs that provide a biological component. These projects are installed near or on marsh shorelines to provide wave protection. Three techniques: gabion mats, concrete onshore armor units, and offshore oyster shell units, have proven to be successful technologies based on anticipated effectiveness and cost, but additional alternatives should be explored to further evaluate the overall effectiveness of these technologies within the coastal zone.

6.4.5 Temperature and Salinity Variations

The tactical deployment of new freshwater diversions has been modeled, but the reality of impacts and first flush phenomena are yet to be realized, as the natural environment will respond to these alterations in flow regime processes and eventually reach a new state that may or may not be stable over time. Oysters are an organism that likely will be closely monitored in response to these new flow regimes and associated salinity fluctuations. The use of bioengineered oyster reefs in diversion areas should be a focus of additional study to determine the sustainable biological nature of breakwater structures within the coastal zone.

6.5 Summary and Conclusion

Biologically dominated engineered coastal breakwaters can overcome many environmental factors in the Louisiana coastal zone and provide additional ecosystem services. These

breakwaters serve as 3D high-relief oyster reefs dissipating wave energy and offsetting sea level rise and subsidence, and can withstand hurricanes. Biologically dominated coastal breakwaters can also serve as oyster broodstock sanctuaries for public seed grounds, improve water quality, sequester carbon, and facilitate ecological recovery within estuarine systems. Optimizing design of these bioengineered artificial oyster reefs can provide a sustainable solution for coastal zone managers.

Bioengineered oyster reefs are an exciting new development in coastal protection and restoration. Existing research at the LSU AgCenter has provided preliminary data necessary to support a large-scale commercial demonstration project now being extensively monitored by state and federal agencies to determine long-term effectiveness for oyster growth and function as a breakwater structure. By becoming biologically dominated over time, the overall effectiveness of these structures will likely improve and they will prove to be a sustainable method for shoreline protection, mitigating land loss in coastal Louisiana. The results of this dissertation support that conclusion, but additional research is needed.

VITA

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His immediate family includes grandparents Wally (deceased) and Alita Keller, Polly and Walter Risinger (both deceased); his parents David J. Risinger and Dr. Bill and Vivian Brent; sisters Kristie Rowland and Alita Prosser. He originates from the Hoppal and Risinger clans, both German pioneer families in the 19th century. Mr. Risinger enjoys water, nature, spending time with friends and family, Donna and his pack of short-stature blue tick beagle sires.